Contract Report 531

Identification of Study Approaches To Determine Physical Impacts of Commercial Navigation on the Upper Mississippi River System

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Office of Hydraulics & River Mechanics

Prepared for the
U.S. Fish and Wildlife Service and
the Illinois Department of Conservation

April 1992

Illinois State Water Survey
Hydrology Division
Champaign, Illinois

A Division of the Illinois Department of Energy and Natural Resources

IDENTIFICATION OF STUDY APPROACHES TO DETERMINE PHYSICAL IMPACTS OF COMMERCIAL NAVIGATION ON THE UPPER MISSISSIPPI RIVER SYSTEM

by

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Funding for this work was partially provided
by the U.S. Fish and Wildlife Service through
the Illinois Department of Conservation

Project Number FWS14-16-0003-80-973

Champaign, Illinois

April 1992

This report was printed on recycled and recyclable papers.

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NOTATIONS

Symbol	*Description*
A	Coefficient
A_b	Submerged tow area
A_c	Channel area
a	Coefficient
B	Channel width
BF	Blocking factor
B/y	Channel shape factor
b	Barge or tow width
C_s	Sediment concentration
C	Coefficient
C_f	Skin friction coefficient
C_w	Wave drag coefficient
c	Coefficient
c	Wave speed
D	Barge or tow draft
D_f	Skin friction drag force
D_p	Propellor diameter
D_r	Draft/depm ratio
D_w	Wave drag force
d	Particle size
E	Factor
e	Base of natural logarithms
F	Propellor thrust
F	Channel Froude number
F_d	Draft Froude number
F_l	Length Froude number
g	Acceleration of gravity
H_d	Bed form size
H/y	Relative wave height
H	Wave height
HP	Towboat power
h_p	Height of propellor axis above bottom
K	Open or ducted propellors
K_f	Thrust coefficient
K_t	Torque coefficient
k	Surface roughness height
k/1	Relative roughness
1	Barge or tow length
1/b	Tow aspect ratio
N	Number of propellors
n	Propellor rotation rate
P	Propellor pitch
P_{kw}	Power in kilowatts
P_r	Power ratio
Q	Discharge
Q_j	Propellor flow rate
R	Radius of curvature
Re_l	Length Reynolds number
Re_c	Channel Reynolds number
r	Radial coordinate in propellor jet

NOTATIONS
(concluded)

Symbol	*Description*
S	Energy slope
$Sg/(yV_8)$	Slope factor
T	Propellor Torque
T	Wave period
T_o	Water temperature
t	Time
t_r	Time ratio
V	Velocity
V:	Propellor jet speed
V_{max}	Maximum or centerline velocity
V_p	Jet velocity at propellor
V_r	Relative tow speed
V_{rx}	Velocity at location x,r in jet
V_8	Average river velocity
V_t	Barge tow speed
V_w	Wind speed
V_r/V_8	Velocity ratio
v'^2/y^2	Turbulence intensity
x	Longitudinal coordinate distance
y	Channel depth
z	Distance to a point
z/B	Relative distance
a	Angle to channel
ß	Bow rake angle
γ	Unit weight
AV	Incremental velocity
Ay	Drawdown
Ay/y	Relative drawdown
δ	Boundary layer thickness
η	Efficiency
A	Wave length
v	Kinematic viscosity
p	Mass density

IDENTIFICATION OF STUDY APPROACHES TO DETERMINE PHYSICAL IMPACTS OF COMMERCIAL NAVIGATION ON THE UPPER MISSISSIPPI RIVER SYSTEM

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INTRODUCTION

The Comprehensive Master Plan for the Management of the Upper Mississippi River System (UMRBC, 1982) recommended that programs for habitat rehabilitation and enhancement, resource monitoring, and a computerized information system be established and funded simultaneously with the design and construction of a 600-foot-long second lock at Replacement Locks and Dam 26 (now called the Melvin Price Locks and Dam). Thus in 1985, in accord with P.L. 99-88, the Upper Mississippi River System Environmental Management Plan came into existence under the supervision of the North Central Division, U.S. Army Corps of Engineers (USACE, 1986). In this report, the Upper Mississippi River System is referred to as UMRS and the Environmental Management Plan is abbreviated as EMP.

The need to obtain better information on the effects of increased navigation on the UMRS ecosystem was stated clearly in the environmental impact statement for the second lock at the Melvin Price Locks and Dam (USACE, 1988). The St. Louis District, U.S. Army Corps of Engineers, is pursuing the development of the plan of study (POS) called for by the environmental impact statement. At this time (April 1991) the POS has been submitted to representatives of five states and the U.S. Fish and Wildlife Service for final comments before the district submits it for approval.

The Habitat Rehabilitation and Enhancement Program (HREP) is being implemented by the Corps of Engineers, with the Rock Island District as the coordinating office. The Long Term Resource Monitoring Program (LTRMP) is being implemented by the U.S. Fish and Wildlife Service through the Environmental Management Technical Center (EMTC) in Onalaska, Wisconsin. The LTRMP consists of four components: 1) evaluation of HREP projects; 2) assessment of long-term trends in selected resources (resource trend analysis, or RTA); 3) assessment of specific resource problems, beginning with a problem identification and analysis process (PIA); and 4) establishment of an integrated database management system (IDMS) based on a geographical information system (GIS). An operating plan for the components of the LTRMP was presented by Rasmussen and Wlosinski (1988) and a revised draft operating plan was prepared more recently by EMTC.

Research topics proposed in the operating plan under the PIA component include: 1) 19 tasks on sedimentation, 2) 15 tasks on navigation effects, 3) 6 tasks on water-level regulation, 4)

9 tasks on lack of aquatic vegetation, and 5) 8 tasks on reduced fisheries populations. Further assessment of the needs for PIA studies has produced the list of sub-problems given in table 1. Sub-problem 1 (single traffic events produce short-term physical changes in channel trough and channel border habitats) is based on a refined combination of two work tasks designated by Rasmussen and Wlosinski (1988) as PA(NE)1 (Determine turbulence and shear patterns in the main channel and turbulence in the main channel border associated with commercial vessel passage by vessel speed, size, direction and river flow and channel characteristics) and PA(NE)4 (Measure the spatial and temporal distribution of changed velocity and suspended sediment conditions in different habitat types of pools 8, 13, 19, 26, the open river or the LaGrange Pool main channel and channel border habitats in relation to passage of commercial tows). The elements of a long-term strategy for Sub-problem 1 are given in table 2.

This report addresses items A.l through A.6, B.l, and B.2 in table 2, which are preliminary steps to research design. The outline of this report closely follows the pattern of table 2.

QUANTIFICATION OF PHYSICAL EFFECTS OF NAVIGATION

Lists of Traffic, Environmental, and Target Variables

Prior to identification of the relationships between vessel movement on a waterway and effects on fish, plants, benthos, plankton, or habitat and environmental conditions conducive to growth and reproduction of aquatic plants and animals, listings must be made of the physical characteristics of the vessels and the riverine environment, and of the physical effects which in turn cause biological effects. Very general articles such as the presentation of overall considerations in waterway system design by McCartney (1986) are useful in conceptual design and in determination of the size of the waterway and the maximum barge tow. Other authors, including Hochstein and Adams (1989), have summarized information from European waterways and specific reaches of North American waterways. Characteristic parameters of vessels and waterways are shown schematically in figures 1 and 2. For simplicity the lists are given below in three sections: barge tow variables, target variables and biological effects, and environmental variables.

Variables Characteristic of Barge Tows

With reference to figures 1 and 2, the physical variables that describe the size and shape of a barge, convoy of barges, towboat, or barge tow are easily identified. These variables are

Table 1. Navigation Sub-problems Being Studied
under LTRMP Problem Analysis

Sub-problems Associated with Single Traffic Events and Water and Sediment

Sub-problem 1. Single traffic events produce short-term physical changes in channel trough and channel border habitats.

Sub-problem 2. Single traffic events increase movement of suspended solids into backwater habitats.

Sub-problem 3. Cold-season single traffic events produce unique or magnified physical impacts.

Sub-problems Associated with Single Traffic Events and Aquatic Populations

Sub-problem 4. Single traffic events increase ichthyoplankton mortality.
Sub-problem 5. Single traffic events increase adult fish mortality.
Sub-problem 6. Single traffic events change habitat use patterns of adult fish.
Sub-problem 7. Single traffic events reduce growth and distribution of aquatic macrophytes.
Sub-problem 8. Single traffic events increase benthic macroinvertebrate mortality.
Sub-problem 9. Cold-season single traffic events produce unique or magnified biological impacts.

Sub-problems Associated with Multiple Traffic Events

Sub-problem 10. High rates of commercial traffic increase background concentrations of suspended solids.

Sub-problems Associated with Fleeting Impacts

Sub-problem 11. Fleeting results in damage to shoreline vegetation.
Sub-problem 12. Fleeting results in damage to mussel beds.

Sub-problems Associated with Recreational Traffic

Sub-problem 13. Waves produced by recreational boats increase bank erosion and suspended solids.

Table 2. Long-Term Research Strategy for Navigation Sub-problem 1: Single Traffic Events Produce Short-Term Physical Changes in Channel Trough and Channel Border Habitats

A. Quantify the relationships between single commercial traffic events and selected physical variables under defined conditions.

1. List commercial traffic variables requiring characterization.
2. List target physical variables and associated biological impacts.
3. List and categorize environmental variables that may influence the relationships between traffic and target physical variables.
4. Develop conceptual impact model(s) and spatial and temporal patterns of concern.
5. Identify the graphical relationships that require quantification.
6. Identify best-available approaches (lab, field studies, models, or combinations) to generate graphs identified in A.5.
7. Conduct controlled (field or laboratory) studies.
8. Synthesize data into working models (with documentation of assumptions and statistical levels of confidence).
9. Confirm reliability of controlled studies and models with field observations.

B. Document existence of physical impact areas on UMRS (Note: these tasks will be completed minimally for trend analysis reaches, with additional reaches being completed as necessary).

1. Define interim target spatial categories and time periods.
2. Define biologically oriented threshold levels for physical changes.
3. Produce aquatic areas maps.
4. Produce bathymetric maps.
5. Produce maps of bed material and other necessary substrate.
6. Based on products from A.1 to A.3, produce additional required maps.
7. Combine products from B.3 to B.6; generate physical threshold impact maps.
8. Combine physical threshold impact maps and biological threshold levels to identify biological problem areas.

C. Identify and evaluate management practices that minimize or eliminate problem areas.

1. List potential management alternatives available to reduce physical impacts.
2. Develop "what-if" models (or modify models from A.8) to evaluate benefits of identified alternatives.

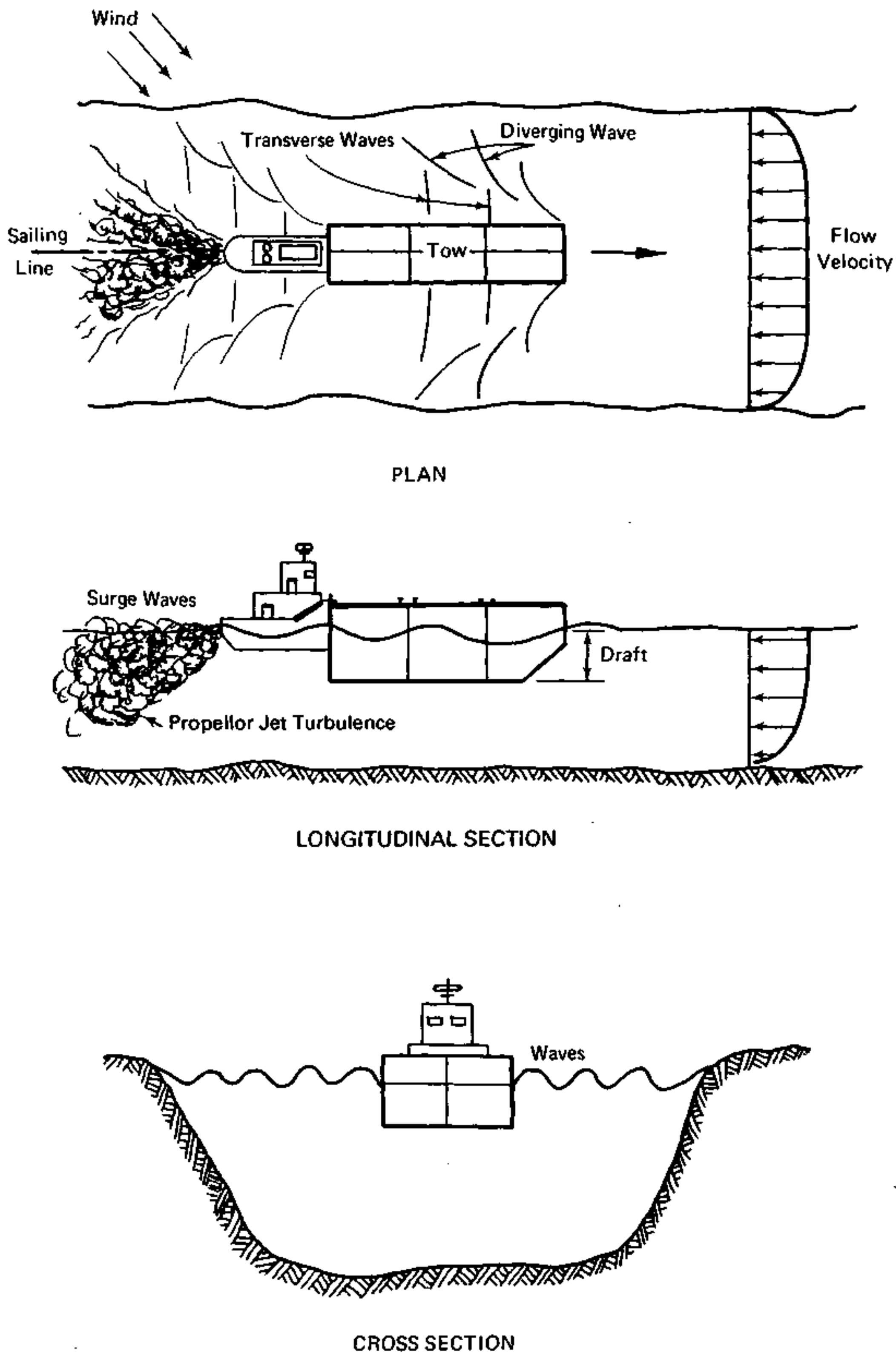

Figure 1. General sketch of barge tow effects

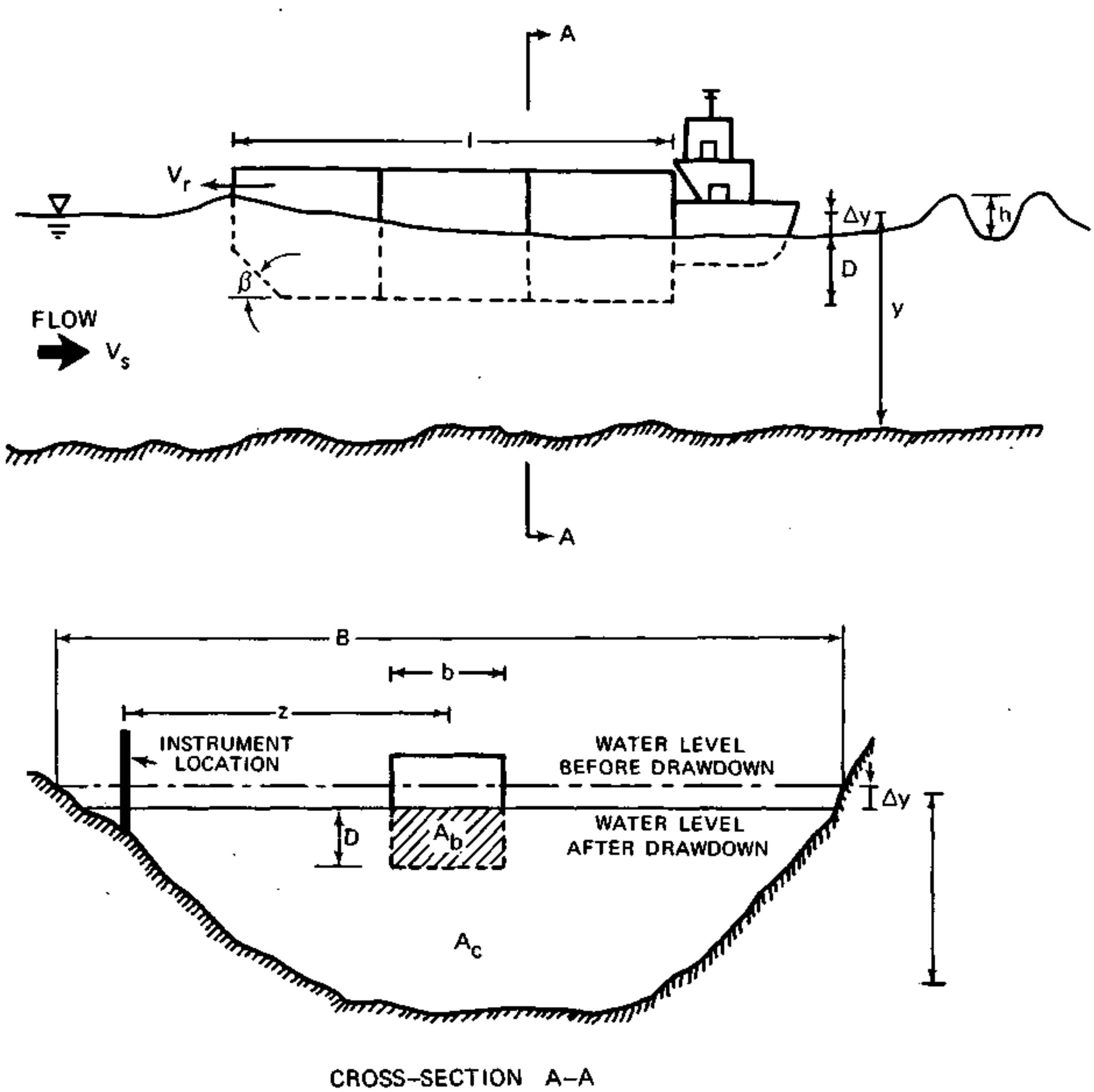

Figure 2. Definition sketch for vessel and environmental variables

listed in table 3 along with typical values for each. A single barge is defined by its length, width, draft, and bow shape. The draft is directly related to the load and load distribution in the barge. Empty jumbo barges have a draft of about 0.61 m (2 ft), which corresponds to a tare weight of about 425 short tons (2000 pounds or 900 kilograms) or 385 tonnes (metric tons). When loaded to the 2.74-m (9-ft) design draft of the waterway, a jumbo barge carries about 1230 tonnes (1350 tons) of cargo. On the UMRS most dry bulk cargo is carried in standard jumbo barges. Petroleum and liquid or gaseous chemicals are carried in tank barges that may be as large as 16.5 m (54 ft) wide by 91.5 m (300 ft) long. There are a great variety of work barges that are generally smaller than cargo barges, but they make up an insignificant part of the commercial traffic on the waterway.

Towboat size is fairly well correlated with horsepower as shown by Latorre (1985). Another variable is the option of open or ducted (Kort nozzle) propellors. Power setting and propellor rotation speed are extremely variable and cannot be included in this general description of vessel movement through the water. However, the distance of the barge tow from a particular point or area of interest, the angle of the tow to a channel centerline, or "sailing line," and the speed of the tow relative to the flow velocity of the river are included here as important characteristics of barge tow travel. Note that these three variables could also be listed in the section on environmental variables.

Target Physical Variables and Biological Effects

The passage of a vessel causes a complex set of primary and secondary effects on the flow pattern in the waterway. Many of the primary effects are identified in figures 1 and 2, and all target physical variables are listed in table 4. The obvious effects are the surface waves generated at the bow and stern and in the wake zone of the vessel as indicated in figures 3 and 4, and turbulent velocities in the propellor jets. Figure 3 shows the various types of waves generated by a moving vessel. Figure 4 shows the definitions for the wave characteristic variables. Less obvious are the flow field developed by the boundary layer along the barge hulls; the "return flow" as the water passes around the barge tow; and drawdown, which is a long wave effect caused by the accelerated open channel conditions and directly related to the velocity of the return flow.

Secondary effects result when the primary effects encounter the river bed, river banks, or a change in channel morphology. They include resuspension of bed material by the accelerated flow or propellor jets; resuspension of bed or bank material by waves; transport of suspended material by the changed velocity field, including turbulence; and changes in velocity, water depth, or flux of suspended material in side channels, tributary mouths, or backwaters.

Table 3. Barge Tow Variables and Ranges

Variable	*Symbol*	*Units**	*Typical values***	
			Minimum	*Maximum*
Barge or tow width	b	L	10.67	32.92
Barge or tow length	1	L	59.5	297.3
Barge or tow draft	D	L	0.61	2.74
Bow rake angle	β	°	30	90
Surface roughness	k	L	0.00005	0.0003
Towboat horsepower	HP	LF/T	600	8,000
Barge tow speed	V_t	L/T	0	8
Propellor jet speed	V_O	L/T	0	15
Propellor flow rate	Q_j	L^3/T	0	80
Number of propellors	N		1	3
Open or ducted propellors	K		no	yes
Propellor diameter	D_P	L	1.25	3.05
Propellor rotation rate	n	1/T	0	4
Distance to a point	z	L	0	1,000
Angle to channel	a	°	0	+ /-90

*L = length; T = time; F = force
**Standard international units

Table 4. Target Physical Variables

Variable	*Symbol*	*Units**	*Typical values*** *Minimum*	*Typical values*** *Maximum*
Velocity	V	L/T	0	10
Turbulence intensity	$v^1$2/V2		0	1.0
Wave height	H	L	0.01	5
Wave length	A	L	1	100
Wave period	T	T	0.3	10
Wave speed	c	L/T	1.5	10
Drawdown	Ay	L	0	0.5
Sediment concentration	Cs		0	500 mg/l
Duration of effect	t	T	0	5,000

*L = length; T = time; F = force
**Standard international units

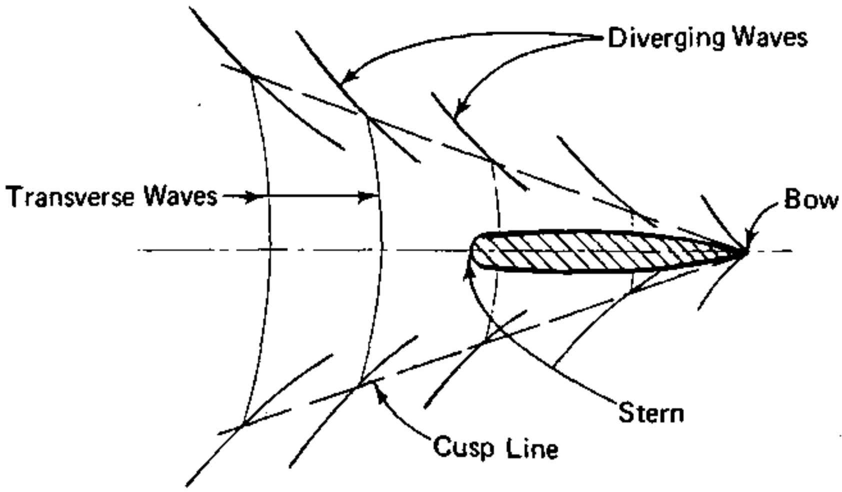

Figure 3. Wave pattern generated by a vessel

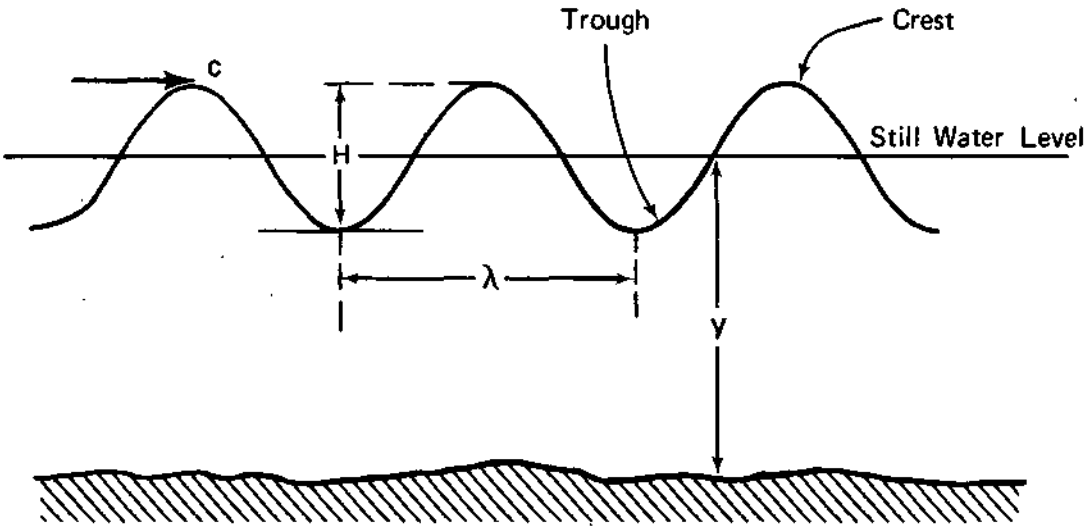

Figure 4. Longitudinal wave profile and wave variables

Biological effects depend on the location, size, and mobility of the organism. Thus plankton and larval fish are essentially free-floating and will be transported with the changed flow velocity or turbulence. There is concern that larval fish in the navigation channel can be hit by the barges or subjected to contact or rapid pressure change as they pass through a propellor. Adult fish presumably will move away from an oncoming barge tow, but may not move far enough to be outside the zone from which flow is drawn through the propellors. Thus for adult fish, contact is unlikely, except by the propellors. Rooted aquatic plants generally colonize shallow-water areas outside the navigation channel, so may not be directly affected by barge tows. However, return flow, drawdown, and wave action can scour material from around their roots and can prevent establishment of seeds or roots. Benthic organisms such as clams and mussels or insect larvae and worms can be affected by velocity and pressure changes if they are living in the navigation channel. In most cases where they inhabit channel border areas, drawdown can expose them to the atmosphere, and sediment resuspended by the propellor jets or waves can affect their feeding ability. Increased deposition of fine sediment may be beneficial or detrimental depending on a particular species response to burial or change in substrate size distribution.

Additional effects of navigation on the biota may occur at some distance from the navigation channel in side channels, backwaters, or tributaries. Such impacts of commercial navigation will be investigated within Sub-problem 2. The biological impacts will each be studied under a specific sub-problem as listed in table 1.

Environmental Variables

Again with reference to figures 1, 2, and 4, there are a number of variables that define the riverine environment and affect the way vessel movement modifies the ambient river conditions. Table 5 lists 12 environmental variables that may be involved in vessel/waterway interactions. The channel cross-sectional geometry is described by width, maximum depth, and horizontal alignment. The depth varies across the channel, and the depth under the barge tow is probably most important but is not known unless the vessel track is known. The vertical and horizontal velocity distribution, including turbulence, and the cross-sectional geometry determine the discharge or volume flow rate of the river. As well as the geometric variables mentioned, the energy slope and bed roughness affect the velocity and turbulence of the river flow. The ambient suspended sediment concentration probably does not enter into any of the relationships, but it may contribute to sediment transport by vessel-induced motion. Temperature is a factor when ice formation is possible, and it affects hydraulic variables through the variation in water density (often negligible) and viscosity. Viscosity is a key factor in sediment transport because

Table 5. Environmental Variables That Affect the Physical Effects of Commercial Navigation

Variable	*Symbol*	*Units**	*Typical values***	
			Minimum	*Maximum*
Maximum channel depth	y	L	0	30
Channel width	B	L	300	2000
Channel area	A_c	L^2	1000	50,000
Energy slope	S	L/L	0	0.001
Velocity	V	L/T	0	10
Discharge	Q	L^3/T	0	30,000
Radius of curvature	R	L	500	infinity
Particle size	d	L	0.000002	0.01
Bed form size	H_d	L	0.01	5
Wind speed	$\mathbf{V}_w$	L/T	0	30
Wind wave height	H	L	0.01	2
Water temperature	T		-4	30

*L = length; T = time; F = force
**Standard international units

of its effect on the fall velocity of particles. The bed material particle size distribution and bed forms such as ripples and dunes will affect the suspension of material by the propellor jets and the flow beneath the barges. Wind and wind waves affect vessel performance and maneuvering, so they play a part in vessel movement effects.

Conceptual Models and Quantitative Relationships

The listing of variables produces a large and hard-to-manage set of variables. The interactions of some variables are easier to visualize than others, but to develop a complete model of the effects of vessel traffic on a river system as large and varied as the UMRS seems impossible. Dimensional analysis is one of the traditional methods used to approach complex problems in hydraulics and fluid mechanics. In dimensional analysis, the requirement that any expression must be dimensionally homogeneous is used to form dimensionless groups and to derive a conceptual form for a particular relationship. Data from field or laboratory measurements are used to quantify the relationship. Frequently dimensional analysis will identify scaling factors mat are important to the processes being described. In the following section a group of variables selected from tables 3, 4, and 5 are used in a dimensional analysis. Additional conceptual relationships are discussed later in the report.

Dimensional Analysis

The rationale for dimensional analysis is the requirement that valid statements of physical phenomena be dimensionally homogeneous. A classic treatise on dimensional analysis was given by Bridgeman (1931). A comprehensive treatment of dimensional analysis in fluid mechanics, including an example analysis of sediment suspension by a stream, is given in the advanced fluid mechanics text by Rouse (1959). All variables have units that are products of length (L), time (T), and mass or force (F) raised to some power. For systems such as river navigation, the process of dimensional analysis not only leads to important ratios of variables, but also reduces the total number of variables by diree, the number of basic units (length, time, and mass).

Most of the variables listed in table 6 are taken from the lists of vessel, physical, and environmental variables in tables 3, 4, and 5. Most of these variables are also shown in figures 1 through 4. The additional parameters in table 6 are fundamental quantities (time and acceleration of gravity) and properties of water (unit weight and kinematic viscosity). Several variables (e.g., sediment concentration) from tables 3, 4, and 5 are not included in table 6 and will be treated separately. Since any diree variables that include all three units may be chosen as

Table 6. Basic Variables and Dimensions

Variable	*Symbol*	*Units**
Channel area	A_c	L^2
Submerged tow area	A_b	L^2
Maximum tow draft	D	L
Maximum channel depth	y	L
Channel width	B	L
Acceleration of gravity	g	L/T^2
Barge tow length	1	L
Towboat horsepower	HP	LF/T
Average river flow velocity	V_s	L/T
Relative tow speed	V_r	L/T
Energy slope	S	L/L
Unit weight	*1*	F/L^3
Discharge	Q	L^3/T
Barge tow width	b	L
Distance to vessel	z	L
Drawdown	Ay	L
Wave height	H	L
Kinematic viscosity	*v*	L^2/T
Surface roughness	k	L
Time	t	T

*L = length; T = time; F = force

the repeating variables, the resulting set of dimensionless parameters is not unique. Engineering judgment and experience are used to select the most appropriate combinations of parameters for each effect of vessel movement.

Following traditional practice for open channel systems, the repeating variables are 1) y, channel depth; 2) V_s, river flow velocity; and 3) γ, unit weight of water. When these three repeating variables were used in a dimensional analysis of the 20 variables in table 6, 17 dimensionless parameters were obtained. After some substitutions and manipulations, a set of parameters, including several standards such as Froude and Reynolds numbers, was developed. These parameters are given in table 7.

The first two parameters in table 7 are the draft/depth ratio, D/y, and the ratio of the submerged cross-sectional area of the barge tow to the channel area, A_b/A_c, which is often called the blocking factor. Some authors (e.g., Hochstein and Adams, 1989) call the inverse ratio, A_c/A_b, the blocking factor. Velocities may appear in simple ratios, but for free-surface flows Froude numbers are often the best velocity parameters. The channel Froude number, F, is the ratio of the average flow velocity to the speed of a wave in water of channel average depth. The draft Froude number, F_d, for the tow may be related to drawdown and return flow velocity, and the tow length Froude number, F_l, is descriptive of tow wave-making characteristics.

The power ratio relates towboat horsepower to the stream power and is based on work by Stefan and Riley (1985). The time ratio is a common parameter for either time or speed related to the size of the vessel, or perhaps to reach length. The relative roughness and length Reynolds number determine the skin friction drag coefficient. The ratio, z/B, of sailing line distance to channel width is used to address variability of wave height, return velocity, and other effects with distance from the vessel track. In shallow water, the ratio of wave height to water depth is important.

Often the actual geometry or kinematics will make the choice of parameters obvious. The tow aspect ratio is included to complete the set of parameters, but it may be more important for maneuvering characteristics of tows than for effects on the waterway. The channel shape factor may be important in constricted waterways, though most of the reaches will be classified as wide (B/y> 10). The ratio of drawdown to channel depth, dy/y, is an obvious dimensionless parameter. The channel Reynolds number, Re_c, is implied in all flow resistance formulae, but waterway flows are turbulent to fully turbulent on the basis of the common values of Re_c and the ratio (k/y) of bed form or roughness height to flow depth. The ratio of vessel to river flow velocity is listed for completeness. Most likely, a Froude number will be a better parameter. Again, the slope factor is included for completeness and would commonly be expressed in terms of one of the flow resistance formulae such as the Chezy or Manning equations.

Table 7. Vessel Passage Parameters

Parameter	*Symbol*	*Definition*
Draft/depth ratio	D_r	D/y
Blocking factor	BF	A_b/A_c
Channel Froude number	F	$V_s/[g(A_c/B)]^{0.5}$
Draft Froude number	F_d	$V_r/(gD)^{0.5}$
Length Froude number	F_l	$V_r/(gl)^{0.5}$
Power ratio	P_r	$(HP/(V_r + V_s))/(wQS\ x/V_s)$
Time ratio	t_r	tV/l
Relative distance	z/B	z/B
Wave height	h/y	h/y
Length Reynolds number	Re,	$V_r l/K$
Relative roughness	k/l	k/1
Tow aspect ratio	l/b	1/b
Channel shape factor	B/y	B/y
Relative drawdown	Ay/y	Ay/y
Channel Reynolds number	Re_c	$V_S(A_C/B)/K$
Velocity ratio	V_r/V_s	$V_r A_s$
Slope factor	$Sg/(yV_s)$	$Sg/(yV_s)$

As specific effects are studied, particular selections of parameters and perhaps different parameters from those in table 7 will be found to be important. The next section gives the range of values to be expected on the UMRS for several of the parameters in table 7 and for several variables dependent on one or more of the parameters.

Typical Values of Selected Dimensionless Parameters

To begin the discussion of conceptual approaches to relate physical effects of navigation to vessel and environmental characteristics, typical value ranges for several parameters will be discussed for barge tows on the UMRS. From table 7, D_r, BF, F_l, P_r, and wave height/drawdown are selected. Vessel drag forces are defined in terms of Froude and Reynolds numbers and relative roughness. An estimation of boundary layer thickness is also made. Propellor jet flows are treated at some length.

Draft/Depth Ratio. D_r, which is the ratio of vessel draft to the maximum channel depth (perhaps the depth on the vessel's track would be better), indicates the clearance below the vessel. The larger this ratio, the larger the amount of water that must be displaced from beneath the vessel and the greater the acceleration of the water between the bottom of the vessel and the river bed. Significant effects can be expected if this ratio exceeds 0.5, i.e., the depth is less than twice the draft. On inland waterways in the United States with a 2.74-m (9-foot) design draft, this depth is 5.5 m (18 ft). The inverse of this ratio is also commonly used.

This ratio is the easiest to calculate since the range of barge drafts is from 0.60 to 2.74 m and channel depths vary from about 3.5 to 15 m. Figure 5 shows D_r values for the common ranges of draft and depth. For the UMRS, operation at D_r above 0.90 for fully loaded barges with 2.74 m draft is likely only near docks or in reaches in need of dredging.

Blocking Factor. The blocking factor, BF, is the ratio of the cross-sectional area of the submerged portion of the vessel, A_b, to the cross-sectional area of the river channel, A_c. Similar to the draft-depth ratio, the blocking factor quantifies the proportion of the cross section available for the river flow and the water displaced by the vessel to pass the vessel. The limiting value for significant effects is considered to be 0.1.

The river cross-sectional area can range from the minimum navigation channel size to much larger values. The moderate range of barge widths and drafts and convoy widths defines the range of values for A_b, from 6.5 to 88 m^2. Figure 6 shows a portion of the total range calculated, and only a small part of this has BF values over 0.1. Each line refers to a particular width of tow in terms of standard jumbo barges which are 10.7 m (35 ft) wide and either loaded or empty. On the Illinois River, a typical cross section has a width of 200 m and an average depth of 3 m, and thus A_c is 600 square meters. The BF values vary from less than 0.009 for a

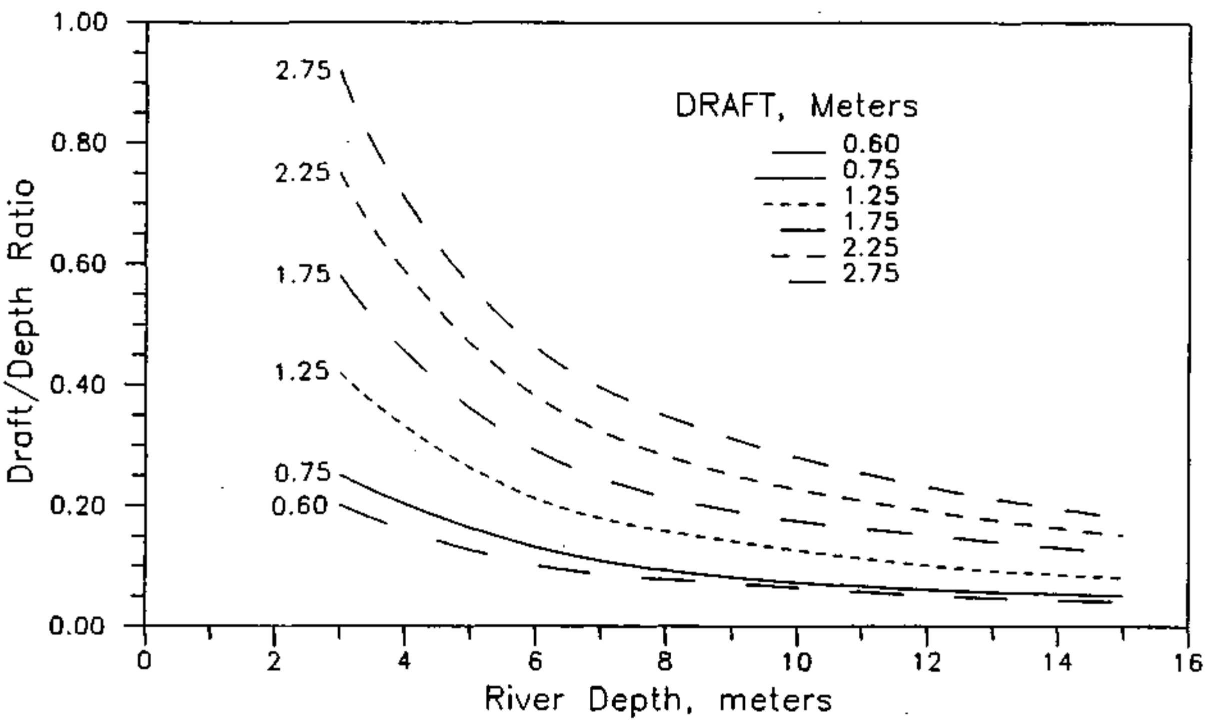

Figure 5. Draft/depth ratios for barge tows
on the Upper Mississippi River System

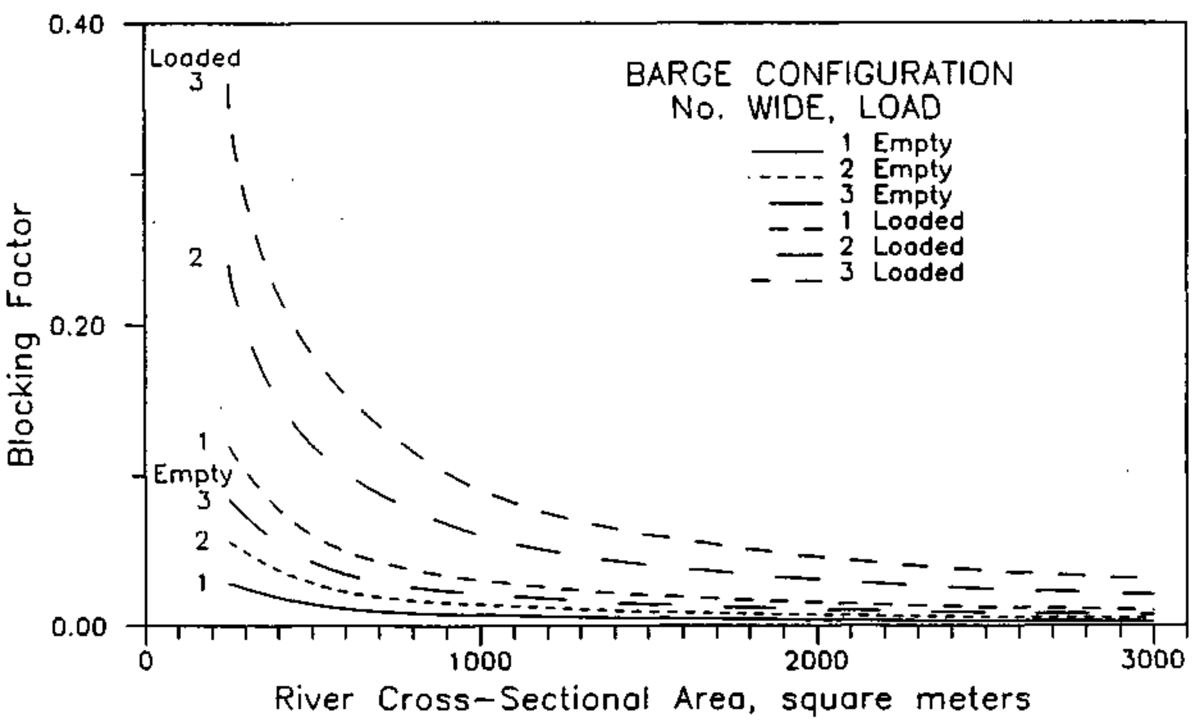

Figure 6. Blocking factors for tows one to three barges wide
on the Upper Mississippi River System

single empty barge to 0.118 for three-wide barges with a draft of 2.74 m. In many reaches of the Mississippi River, the width is about 450 m and the average depth is about 5 m. For such a cross section, the area is 2,250 square meters, and BF values vary from 0.003 to 0.042 for the same range of barge tows used for the Illinois River.

Because of the variability in channel width and depth, and the change in depth with discharge, it is difficult to define critical reaches without specific geometric information. Channel geometry also depends on curvature and flow bifurcation at islands. When applied to estimate drawdown and flow velocity at a point, the distance of the sailing line from the point of interest is important as well as BF and D_r.

Length Froude Number. The Froude number is the primary parameter identifying wave conditions and flow in open channels. The movement of vessels in rivers involves both of these phenomena. The flow of rivers is generally tranquil, or subcritical, based on a Froude number with the depth as the length factor ($F_d = V_S/(gy)^{0.5}$). The change in this Froude number caused by the passage of a vessel is an indicator of the amount of acceleration caused by the vessel and is directly related to the blocking factor.

The length Froude number, Fj, is an important parameter describing vessel resistance and wave-making characteristics. There is a change in wave patterns if the Froude number based on vessel speed and water depth equals 1, but this is highly unlikely for barge tows. Some recreational vessels exceed this condition, above which transverse waves in the wake are not formed. For convoys of standard jumbo barges, the range of F_l is shown in figure 7a. The upper values are in a range of increasing wave-making drag which peaks at F_l - 0.5. Note that cabin cruisers and towboats without barge convoys are not represented on this figure. Smaller craft mat can plane will have $F_l > 1.0$. Length Froude numbers for recreational boats and towboats are shown in figure 7b. Again, towboats will have F_l values less than about 0.5, and only small, fast boats will travel at an $F_l > 1.0$.

Power Ratio. The power ratio relates the energy transmitted to the river by the towboat to the energy expended by the river in overcoming friction. Both factors vary over wide ranges. For discharges between 150 and 7,500 cubic meters per second (cms), with typical energy slopes and velocities, the energy expended by the rivers of the UMRS increases from about 20 to 1,250 joules per meter (J/m) of channel length. Note that 1 joule is defined as 1 watt-second. The values of discharge, slope, and velocity used are given in table 8. Each reach of the waterway will have its own hydraulic characteristics.

The energy transferred from a towboat per meter traveled depends on many factors such as installed horsepower, propellor characteristics, overall power train efficiency, speed, load, and acceleration. To estimate mis factor, the horsepower is assumed to range from 500 to

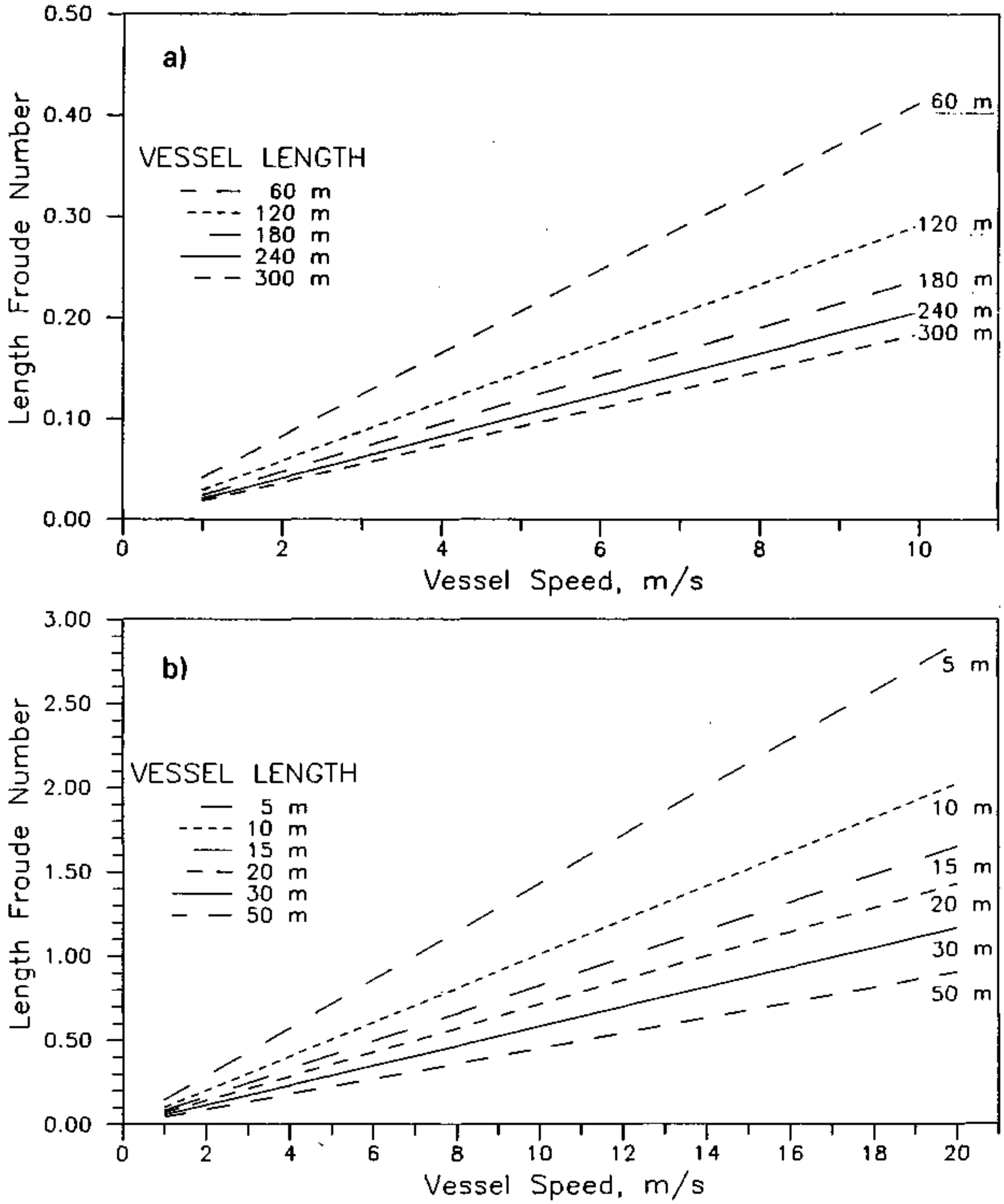

Figure 7. Length Froude Numbers, $F_1 = Vr/(gl)^{0.5}$, for a) barge tows and b) recreational boats and towboats

Table 8. River Conditions Used to Generate Power Ratios

Discharge, cms	*Slope*	*Velocity, m/s*	*Energy, J/m*
150	0.00002	0.15	20
300	0.00002	0.15	40
750	0.00004	0.30	100
1500	0.00008	0.60	200
3000	0.00016	0.90	533
7500	0.00020	1.20	1250

7,000, and the absolute tow speed between 0.3 and 8 m/s (1 to 29 kph, 0.7 to 18 mph, or 1 to 26 fps).

These conditions yield a range of energy expenditure from 47 to 17,400 kilojoules per meter (kJ/m) as given in table 9. Note that the rated power is used in P_r without any allowance for power setting, efficiency, or load. The energy per meter of travel transmitted to the river by a 500 HP towboat moving 4 m/s is equivalent to the energy expended by the river with a discharge of 7,500 cms in about 74 m of channel length. A 7,000 HP towboat at full power, moving 0.3 m/s, expends energy equivalent to about 870 km of river for the 150 cms low-flow condition. These values are actually the inverse of P_r as defined in table 7. Figure 8 shows the trend of $1/P_r$ as a function of discharge and towboat power per meter. Note that the slope and velocity conditions for a given discharge are as given in table 8 and the towboat horsepower (kilowatts) and absolute speed are as given in table 9. The power transferred to the waterway by a towboat ranges from about 100 to 1,000,000 times the stream power for conditions on the UMRS.

Drawdown Drawdown is the decrease in water depth caused by the increased flow velocity resulting from the blocking of part of the channel cross-sectional area by the submerged area of the vessel. Bhowmik et al. (1981b, 1982) reviewed several published expressions for drawdown. Schijf and Jansen (1953) derived two equations for drawdown, Ay, and return velocity, AV, from Bernoulli's equation and the continuity equation:

$$Ay = [(V + AV)^2 - V^2]/2g \qquad (1)$$

and $$VA_C = (V + \Delta V)[A_c - A_b - (BAy) \qquad (2)$$

These two equations can be solved simultaneously to give Ay and AV. Bhowmik and colleagues (1981b, 1982) also derived their own equation for drawdown on the basis of regression analysis of data from 27 measurements on the Illinois and Mississippi Rivers. This equation is:

$$Ay/Y' = 0.478(F_{Y'})(BF)^{0.81} (1/z)^{0.26} \qquad (3)$$

where Y' = y - D, 1 = tow length, and z = distance from tow.

They reported a better correlation coefficient for this equation man for the methods proposed by Schijf and Jansen (1953), Dand and White (1978), Gates and Herbich (1977), and Gelencser (1977). Hochstein and Adams (1989) give an equation based on data from Russian canals which does not fit the data of Bhowmik and colleagues (1981b, 1982).

Table 9. Unit Towboat Power, kJ/m

Horsepower	*kw*	*Absolute towspeed, m/s* 0.3	0.6	1.0	2.0	4.0	8.0
500	373	1243	622	373	187	93	47
1000	746	2487	1243	746	373	187	93
2000	1492	4973	2487	1492	746	373	187
3000	2238	7460	3730	2238	1419	560	280
4000	2984	9945	4973	2984	1492	746	373
5000	3730	12433	6217	3730	1865	933	466
6000	4476	14920	7460	4476	2238	1119	560
7000	5222	17407	8703	5222	2611	1306	653

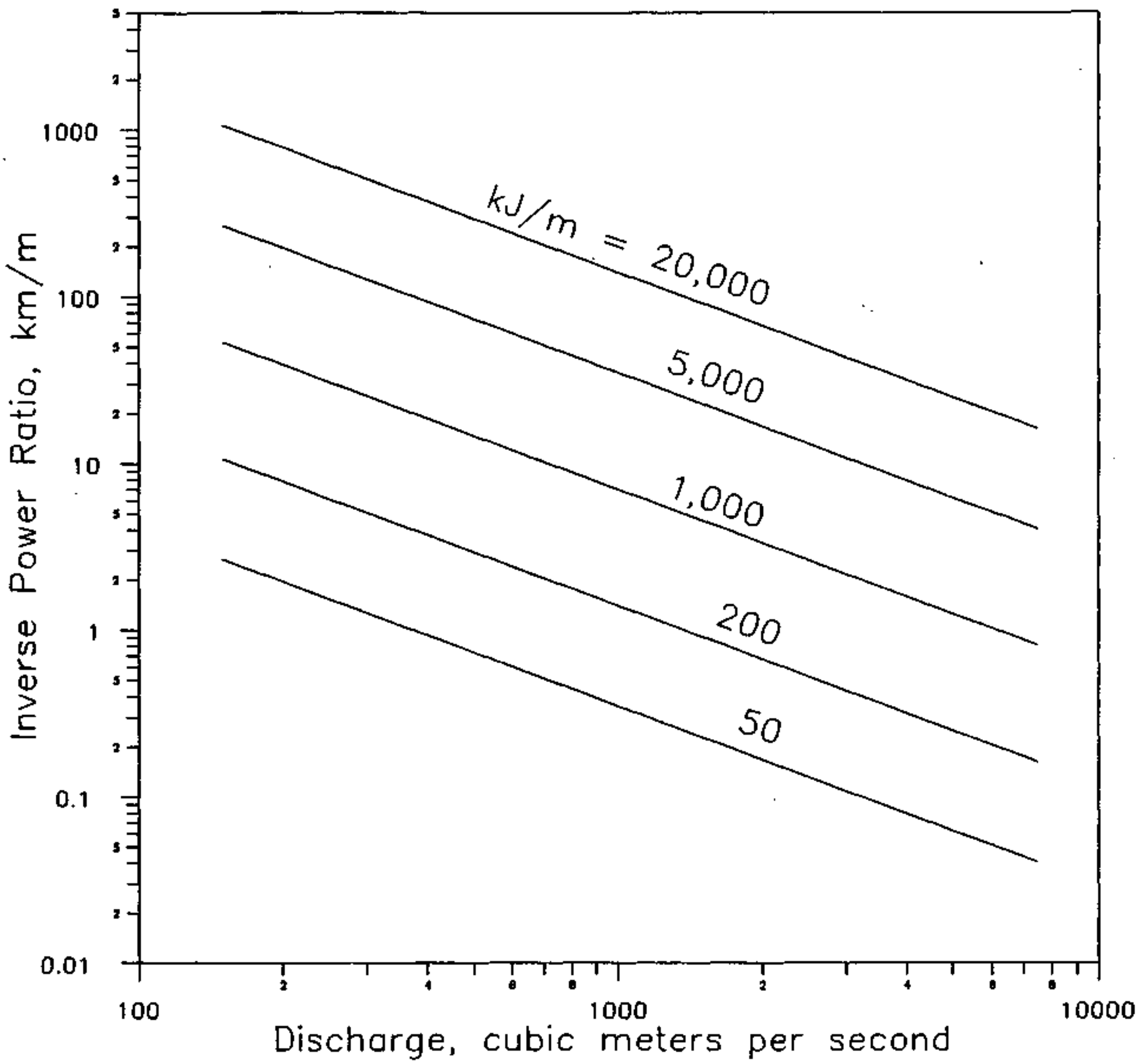

Figure 8. Inverse power ratio as a function of river flow rate and towboat power/speed ratio

The equation of Bhowmik et al. (1982) includes all the parameters an intuitive approach might include, and they are consistent with the basic equations as given by Schijf and Jansen (1953). The Froude number accounts for the tow speed and the depth of water beneath the tow. The blocking factor has a direct effect, with $BF^{0.81}$ varying from 0.0037 to 0.27 for BF values from 0.001 to 0.2. The drawdown will decrease gradually with distance from the tow as shown by the factor $(1/z)^{0.26}$, which takes on values from 1 to 2.8 for l/z values from 1 to 50. Although the tow length was chosen as the reference length, other variables such as tow width or channel width may also be appropriate. Another Froude number might be found to be better in a future analysis. The equation of Bhowmik et al. (1982) was obtained by multiple regression, and the most significant parameters were retained in the recommended equation.

Wave Height. Bhowmik and colleagues (1981b, 1982) also reviewed available equations for the height (from trough to crest) of ship-generated waves. They reported two equations, one by Balanin and Bykov (1965) and one by Hochstein that was unpublished until 1989 (Hockstein and Adams, 1989). Neither equation yielded estimates that agreed well with the field measurements of Bhowmik and colleagues (1981, 1982), so they used multiple regression to obtain the following equation:

$$H_{max}/D = 0.133\ F_d \qquad (4)$$

which better represents their data. Wave height is expected to decrease with distance traveled as reported by Bhowmik (1976), approximately with the square root of the distance from the boat, $(z/l)^{-0.46}$ For each additional 10 boat lengths from the boat track, the wave height will be reduced by 65 percent.

Several other wave characteristics may be important in determining the impacts of vessel-generated waves on the UMRS. Figure 4 shows several cycles of a wave train. In addition to the wave height, H, and water depth, y, the illustration shows the wave length, A, and wave speed, c (commonly called celerity). The wave speed is a function of water depth and wave length, given exactly by Morris (1963):

$$c = [(g\lambda/2\pi)\tanh(2\pi y/\lambda)]^{0.5} \qquad (5)$$

In deep water ($y/\lambda > 1/2$), $\tanh(2\pi/\lambda) = 1$, and $c = (g\lambda/2\pi)^{0.5}$. For very small values of y/A ($y/\lambda<0.015$), the speed becomes independent of wave length, and $c = (gy)^{0.5}$, the denominator in the channel Froude number. The wave period, T, is given by:

$$T = \lambda/c \tag{6}$$

These equations are derived for uniform, sinusoidal waves of small amplitude. Actual wind- and boat-generated waves on oceans, lakes, and rivers are of variable height, length, speed, and period. A typical example of barge-tow generated drawdown and waves is shown in figure 9. A slight increase in water level is noted first as the tow pushes water ahead. This is followed by the drawdown, which extends across the channel along the length of the tow. After the drawdown has ended (or as it decreases, depending on distance to the tow), the diverging waves (see figure 3) arrive at the measuring point. The duration of drawdown is approximately equal to the time it takes the barge tow to pass (about 60 seconds in figure 9). Frequently the waves increase in height to a maximum which is only one or two waves long and corresponds to the diverging waves from the bow of the tow. In some cases another, minor maximum wave is observed from the stern of the last barge. After the towboat stern waves have passed, the wave height gradually returns to that of the ambient wind wave. The drawdown is a single transverse wave caused by the hydraulics of flow around the barge tow. The bow and stern waves move out from the vessel at an angle of about 20 degrees. Thus, though drawdown and waves are caused by the movement of the same vessel, their time of arrival at a given point depends on the distance from the vessel.

Barge-Tow Drag Forces. For movement at steady velocity (no change in speed or direction width time), vessel drag is due to two phenomena: wave-making and surface or skin friction. In naval architecture, the traditional approach has been to determine the wave-making resistance from physical model studies in tow tanks and to calculate the skin friction by using boundary layer theory. Skin friction drag of ships is generally computed by using the total skin friction coefficient, C_f, for a hydrodynamically rough flat plate. The value of C_f is a function of the relative roughness of the plate (k/1) and the length Reynolds number, Re_1. This topic is thoroughly treated in textbooks such as that by Schlichting (1968), as well as in marine engineering literature. This discussion follows a monograph by Pien and Moore (1963). The length Reynolds number is in the range from 10^7 to 10^9, and k/1 is between $5(10)^{-5}$ and $5(10)^{-6}$ for typical barge convoy sizes and speeds. Thus for barge convoys the value of C_f is between 0.002 and 0.003, and a value of 0.0025 may be used. The skin friction drag is given by:

$$D_f = \rho V_r^2/2\, C_f(b + 2D)\, l \tag{7}$$

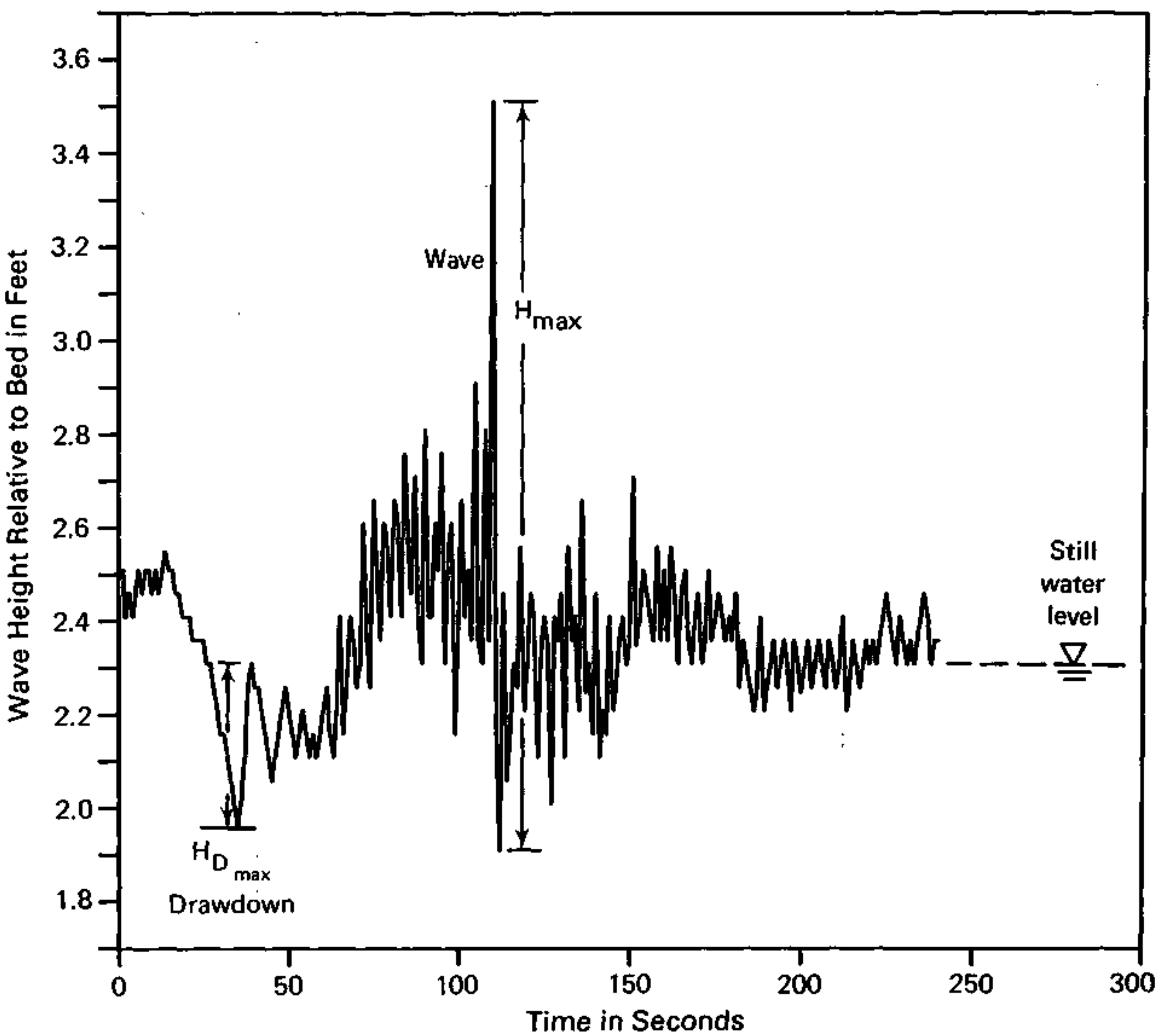

Figure 9. Typical wave and drawdown trace during a barge tow event

The wave drag is commonly determined by subtracting the calculated skin friction from the total drag measured for a model in a towing tank. The wave drag is a nearly linear function of F_l for $F_l < 0.25$ and is determined with this equation:

$$D_w = \rho V_r^2/2\ C_w\ l^2 \qquad (8)$$

As F_l increases above 0.25, the wave drag increases rapidly with peaks around $F_l = 0.5$ and 1.0. Barge tows usually have $F_l < 0.3$, so the following linear relation for C_w may be used:

$$C_w = 0.0005\ F_l \quad \text{for } F_l < 0.3 \qquad (9)$$

Drag and required effective horsepower can be calculated for barge convoys of any configuration and speed. The wave drag is the same for both empty and loaded barges at the same speed. Skin friction increases linearly with increased wetted area, but it increases with the square of speed.

A boundary layer increases in thickness with distance, x, along a surface. For barge tows the length Reynolds number, Re_l, is approximately 10^9 and the boundary layer is turbulent over almost the entire lengdi. For a boundary layer in a flow with zero pressure gradient, the boundary layer thickness is given by:

$$S = 0.38\ x\ (Re_x)^{-1/5} \qquad (10)$$

The reduced velocities within the boundary layer effectively displace some of the flow out of the boundary layer. The displacement uiickness is given as $S = 5/8$. Typical values for S range from approximately 0.5 m at x = 61 m to 1.83 m at x = 305 m. The values for $\delta/8$ are 0.06 m and 0.23 m for x = 61 and 305 m, respectively. In waterways of limited depth, there will be a pressure gradient along the bottom of the tow, and the uiickness of the boundary layer will be greater if the pressure increases with distance or less if it decreases.

Propulsion by Propellor

As mentioned in the discussion of the power and energy ratios, it is very difficult to determine the actual energy transferred to the water by a boat propulsion system. The propulsion system, whether open propellor, ducted propellor (Kort nozzles), or water jet, does not change the basic mechanics. Fundamental discussions of the mechanics of propellors are found in many hydraulics textbooks and treatises. Daily (1950) gives a good and adequately complete discussion. Each system provides certain advantages in terms of efficiency, shallow draft, or economical construction. The basic mechanics of a propellor are shown in figure 10 without the complications of boat hull and proximity of channel bottom. Two other quantities not shown in figure 10 are the rotation speed, n, in revolutions per second, and the pitch, P, in feet of advance per revolution. The momentum equation relates V_r, dV, and the efficiency, η, in the following equation:

$$V_p = V_r/H, \tag{11}$$

It can also be shown that:

$$V_p = V_r + \Delta V/2 \tag{12}$$

A parameter closely related to the propulsive force, or thrust, produced and the efficiency is the speed ratio, V_r/nP. Higher force is produced at low values of this ratio, and the efficiency is higher at high values of the ratio. The propulsive force, or thrust, is proportional to the square of the speed of rotation and to the fourth power of the diameter.

Dimensionless performance curves are shown in figure 11. In this figure the speed ratio is J, or V/nDp, instead of V/nP. The efficiency is η. The torque coefficient is:

$$K_t = T/(\rho n^2 D_p{}^5) \tag{13}$$

and the thrust coefficient is:

$$K_f = F/(\rho n^2 D_p{}^4) \tag{14}$$

Efficiency increases nearly linearly with the speed ratio up to about 0.4, peaks at a speed ratio near 0.85, and then decreases rapidly to 0 at a speed ratio of 1.125. On the other hand, K_f decreases linearly from a maximum at 0 speed ratio to 0 at a speed ratio of 1.125. Maximum thrust is thus maximum for full rpm and zero vessel speed through the water. However, the power transferred to the water is a maximum at a small, but non-zero, speed through the water, and decreases monotonically to 0 at the maximum speed ratio. The useful power that is expended accelerating or moving the vessel has a maximum at an intermediate speed ratio where the product of force and speed is maximum. The relationship between propulsive thrust and total drag force is discussed in a following section.

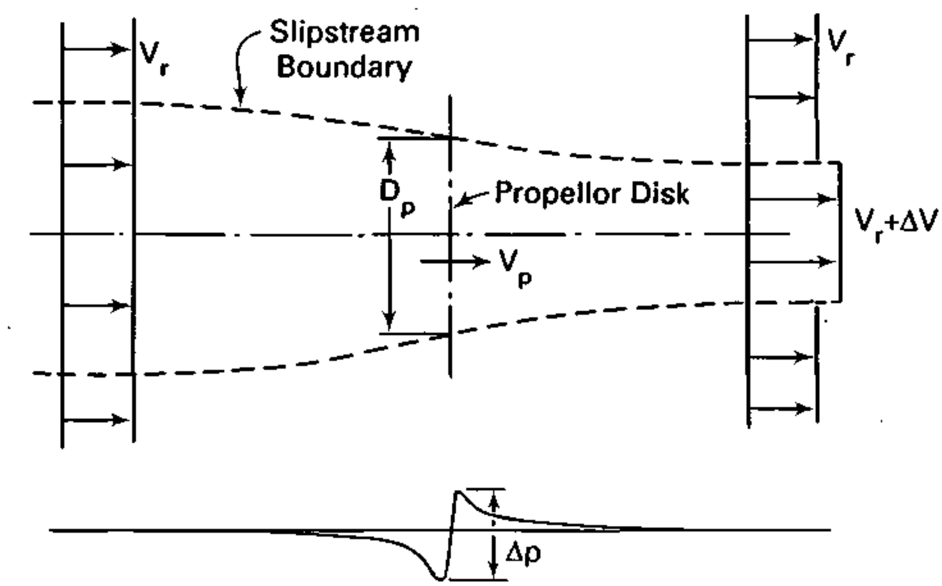

Figure 10. Schematic diagram of axial flow past a propellor

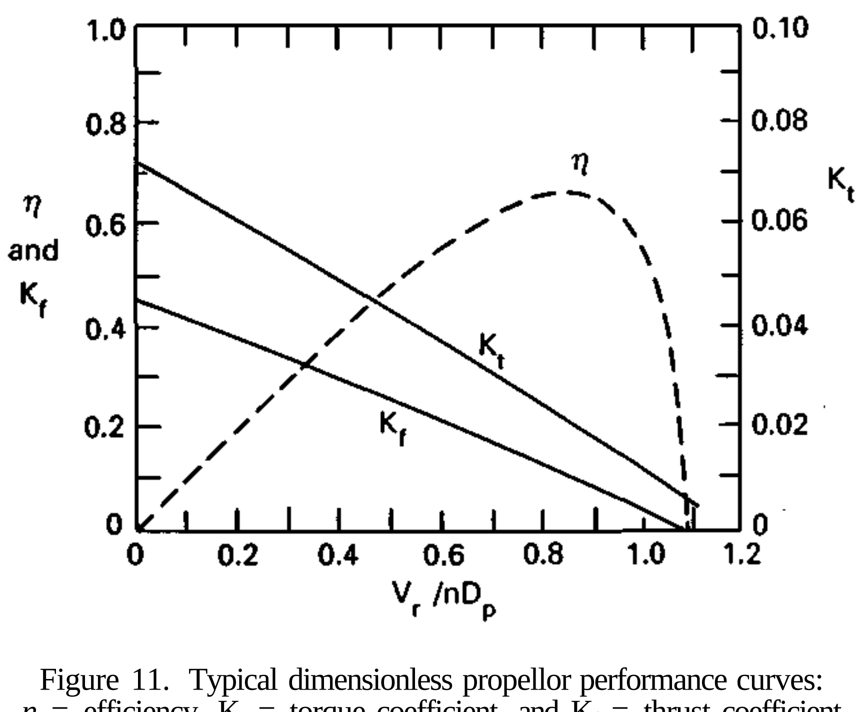

Figure 11. Typical dimensionless propellor performance curves:
η = efficiency, K_t = torque coefficient, and K_f = thrust coefficient

The small depth at which boat propellors are set in most surface vessels, including all vessels that travel on constricted waterways, implies that cavitation may limit the maximum values of dV and V_p. Speed through the water and propellor diameter and rotation speed affect the actual velocity of the propellor blade tips. Cavitating speeds are about 35 fps (11 m/s) for typical propellor shaft depths. Larger-diameter propellors have lower maximum rotation speeds to avoid cavitation and the resulting power loss.

Forces to be overcome by the propulsion system are the skin friction and wave drag of steady motion and the force needed to accelerate or change the velocity of the vessel. In geared diesel and gasoline engine drives, the throttle setting is the only control of propulsive power available. An increase in throttle setting causes an increase in engine speed and thus in propellor speed. This decreases the speed ratio and increases the propulsive force. The vessel then accelerates at a rate proportional to the thrust available in excess of the total drag force until a new equilibrium, or balance, between propulsive force and drag force is reached. Directional changes are made by using rudders within the propellor jets and, for twin screw vessels, by using the differential power or rotation direction setting on each propellor. Recreational boats typically turn the propellor jet direction to change the direction of travel.

A review of the *Inland River Record, 1988-1989* (Owen, 1988) found that 3,500 HP is a maximum for a single engine and propellor unit. Towboats generally operate at low values of the speed ratio and thus of efficiency. Typical values of η are between 0.2 and 0.4, according to Latorre (1985).

Two choices are possible at this point. One is to develop hypothetical barge-tow drag force and propellor thrust values for typical conditions on the UMRS. The section on barge-tow drag forces presents the information needed to compute the drag forces. The other approach is that presented in a paper on towboat characteristics by Latorre (1985). Latorre and Warinner (1986) also published a paper on barge-tow drag. These two papers will be used to illustrate the interaction between barge-tow drag and towboat thrust to move a given barge convoy at a constant speed through the water.

Latorre and Warinner (1986) proposed a modification of the Howe equation (Howe et al., 1969) for shallow-water operation by the addition of the last term:

$$D_f = (0.073) \quad e^a V_r D^c l^{0.38} b^{1.19} \quad + 7{,}200(V_r - 6.0)^{1.56} \tag{15}$$

for $V_r > 6$ mph, with $a = 1.46/(y - D)$, $c = 0.6 + 50/(B - b)$, and the other terms as they were previously defined. Note that this equation is in English units. For use here the last term is modified for convoys of one to fifteen barges by the insertion of the factor (n/15), with n equal to the number of barges in the convoy. Increasing the width of the convoy has a greater effect than increasing the length. For example, two barges can be added to a two-by-two convoy of four barges by increasing the length from two to three barges for an increase in drag of 17 percent or by increasing the width from two to three barges for an increase in drag of 62 percent. Increasing speed raises the drag force in proportion to the square of the speed. The effects of changes in channel depth and width are contained in the exponents a and c and will be shown in some graphical examples.

Latorre (1985) gives an equation for the towboat thrust:

$$F_t = A\ HP\ [1 + 0.142(y/D - 1.78)](1.0 - E\ V_r^2) \tag{16}$$

with A = 15 for open propellors and 19 for Kort nozzles, and E = [0.00744 - 0.0052(HP/10,000)]. This equation yields reduced thrust for depths less than 16 feet for loaded barges with a 9-foot draft, and increased thrust for depths over 16 feet. Also the thrust decreases in proportion to the square of the speed as indicated above in the discussion of the speed ratio.

These equations were applied to a range of convoy sizes for both loaded and empty barges, three towboat horsepowers, either open propellors or Kort nozzles, and three different channel dimensions. The number of barges ranged from one to fifteen and the drafts were 0.76 m empty and 2.74 m loaded. Twin-screw towboat horsepowers were 1,000, 3,000, and 5,000. The 1,000 HP towboat is a typical switch boat and would rarely push a large barge convoy any distance. The 3,000 HP towboat is the average line-haul tow seen on the Illinois River and is also common on the Upper Mississippi River. The 5,000 HP towboat is typical of modern, high-horsepower towboats on the Upper Mississippi River, a majority of which have Kort nozzles. The three channels were 1) 3.66 m deep by 183 m wide, 2) 4.57 m deep by 183 m wide, and 3) 6.10 m deep by 305 m wide.

Since the effect of constricted channel dimensions was much more significant for the loaded barges, figures 12a through f show barge convoy total drag force and towboat thrust in kilonewtons for loaded barges in each of the three channels. Equilibrium speeds in meters per second are given in table 10 for a range of convoy sizes. Note that one m/s is about 2.2 mph. Loaded barges with 2.74-m draft increase drag and reduce thrust such that speed reductions up to 13 percent were computed. Though Kort nozzles increase the thrust by 26 percent, the speed increase over open propellors is less than 10 percent.

Jolson and Bastian (1983) did a statistical analysis of tow characteristics and performance on inland waterways in the United States. They reported average underway speeds. for the Illinois River (upstream 1.80 m/s and downstream 2.21 m/s), and for the Upper Mississippi River (upstream 2.45 m/s and downstream 3.36 m/s). The standard deviations were

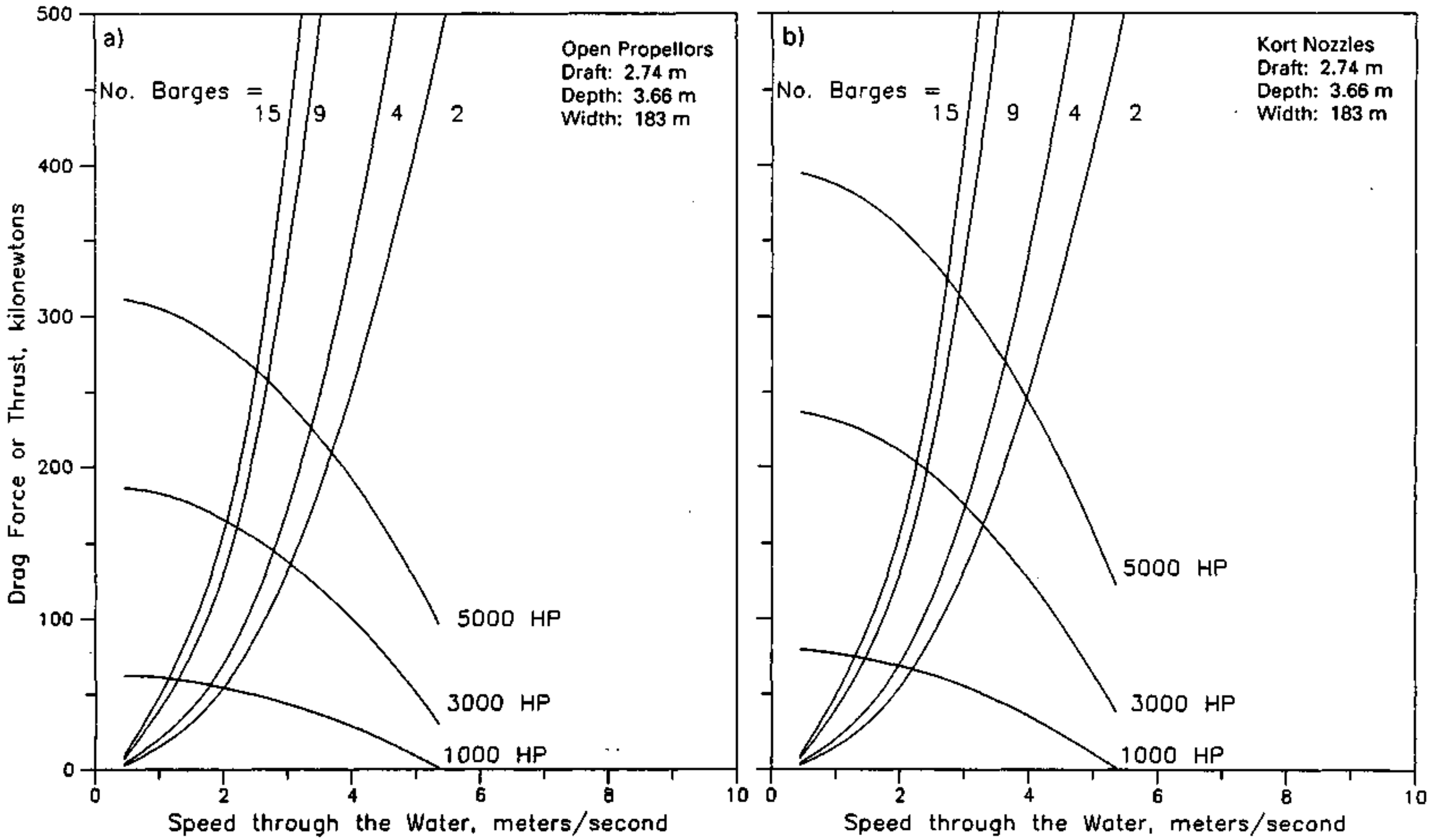

Figure 12. Barge tow performance curves for loaded barges with open propellors and Kort nozzles in channels of different depths and widths

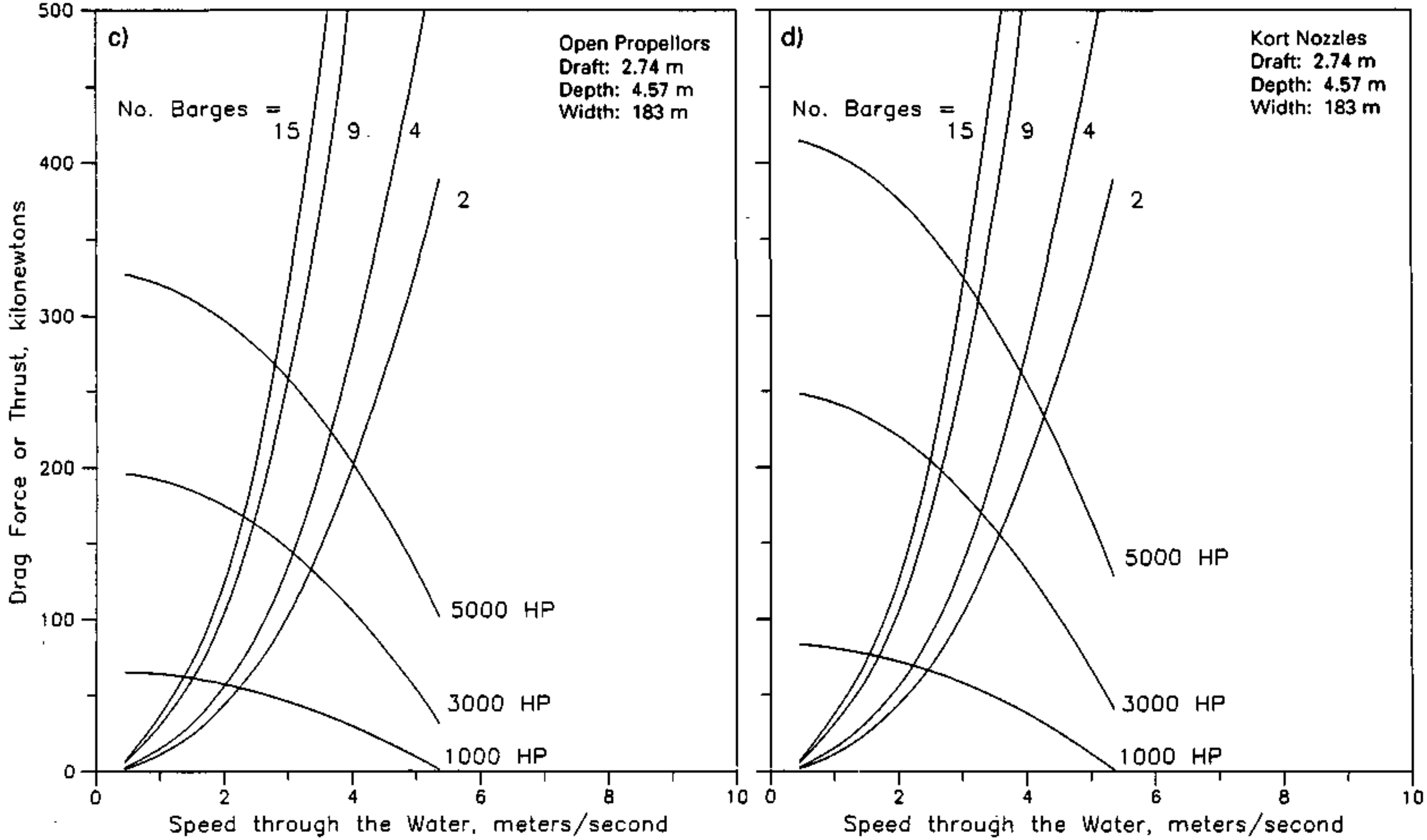

Figure 12. Continued

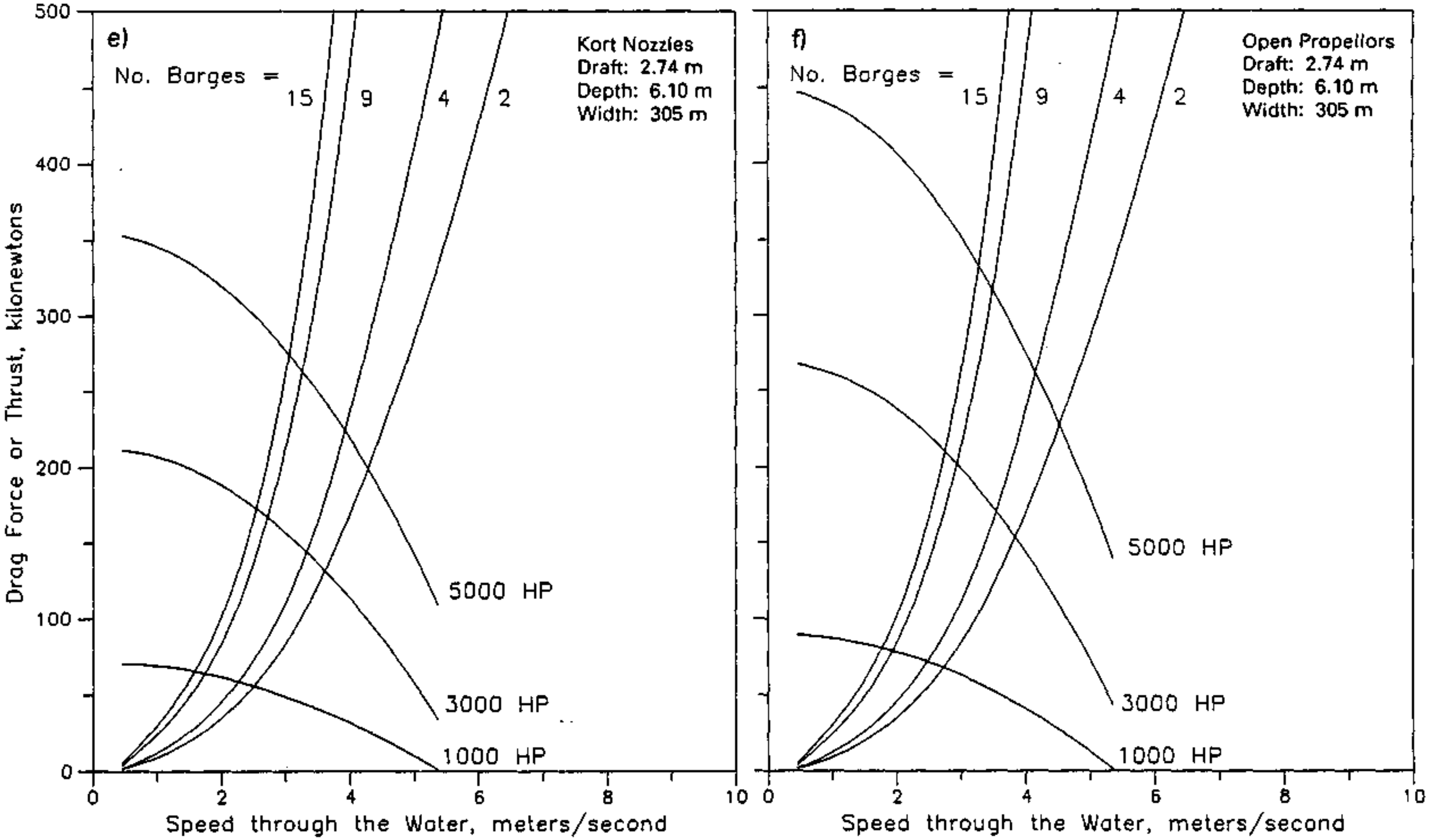

Figure 12. Concluded

Table 10. Equilibrium Speed, m/s, for Typical Barge Convoys, Towboats, and Channel Dimensions

Number of barges	*1000 HP* *Open*	*1000 HP* *Kort*	*3000 HP* *Open*	*3000 HP* *Kort*	*5000 HP* *Open*	*5000 HP* *Kort*
I. 3.66 m deep, 183 m wide						
A. Empty, D = 0.76 m						
2	3.1	3.2	4.1	4.3	4.8	5.0
4	2.8	3.0	3.8	3.9	4.3	4.6
9	2.3	2.5	3.3	3.5	3.8	3.9
15	2.1	2.3	2.1	3.4	3.6	3.8
B. Loaded, D = 2.74 m						
2	2.0	2.2	3.0	3.3	3.7	4.0
4	1.8	2.0	2.8	3.0	3.4	3.6
9	1.3	1.5	2.2	2.4	2.7	2.9
15	1.1	1.3	2.1	2.3	2.5	2.7
II. 4.57 m deep, 183 m wide						
A. Empty, D = 0.76 m						
2	3.1	3.3	4.2	4.3	4.8	5.0
4	2.9	3.1	3.8	4.0	4.4	4.6
9	2.4	2.6	3.4	3.5	3.8	4.0
15	2.2	2.4	3.2	3.4	3.7	3.8
B. Loaded, D = 2.74 m						
2	2.2	2.5	3.3	3.6	4.0	4.3
4	2.0	2.2	3.1	3.3	3.7	3.9
9	1.5	1.7	2.5	2.7	3.0	3.2
15	1.4	1.5	2.3	2.5	2.8	3.0
III. 6.10 m deep, 305 m wide						
A. Empty, D = 0.76 m						
2	3.2	3.4	4.3	4.5	4.9	5.2
4	3.0	3.2	3.9	4.1	4.5	4.7
9	2.5	2.7	3.5	3.6	3.9	4.1
15	2.3	2.5	3.3	3.5	3.8	3.9
B. Loaded, D = 2.74 m						
2	2.5	2.7	3.6	3.8	4.3	4.5
4	2.3	2.5	3.3	3.6	3.9	4.2
9	1.8	2.0	2.7	2.9	3.3	3.5
15	1.6	1.8	2.5	2.8	3.1	3.3

0.87 m/s upstream and 1.14 m/s downstream on the Illinois River and 1.52 m/s upstream and 1.21 m/s downstream on the Upper Mississippi River. They gave the average number of barges per tow as about 11 for both rivers. These are average underway speeds and are in the same range as the computed through-water speeds given in table 10.

Whether wave-making resistance and calculated friction drag are added, or empirical equations of the Howe type are used, the calculation of barge convoy drag is an estimate. The linear estimate of the dependence of drag on the number of barges has not been verified. Smoothness and fouling of barge hull surfaces, imperfect alignment between barges, effects of irregular channel geometry, and wind drag are not considered in the calculations. Similarly, the empirical equation for towboat thrust applies only to steady operation, not to accelerating, turning, or other maneuvering.

Three specific quantities that depend on the propellor operation are of particular interest because of their effects on the movement of water in the channel. The three are closely related, but each conveys a different effect. They will be discussed in the following order: first, the flow rate through the propellors; second, the "intake" area, or portion of river cross section influenced by inflow to the propellor; and finally, the velocity of the jet behind the propellor.

Propellor Flow Rate One factor of interest related to towboat propulsion is the quantity of water mat is drawn dirough the propellors and its relation to the flow rate of the river, or perhaps to the volume of water in a river reach. Latorre's (1985) equation for thrust was used to compute thrusts for the same three towboat horsepowers used above at several values of V_r, the speed dirough the water. This equation was derived for speeds less man 12 mph (5.37 m/s), and gives zero thrust at 14.4 mph. Basic propellor theory was then used to obtain the velocity and flow rate mrough the propellors. Note that the total thrust is assumed to be equally divided between the two propellors for steady motion.

The results give a good indication of the flow rates and area of influence for a particular speed of the tow dirough the water. Propellor flow rates for twin-screw towboats vary from 12 to 20 m^3/s for 1,000 HP, from 31 to 48 m^3/s for 3,000 HP, and from 47 to 75 m^3/s for 5,000 HP. The difference in flow rate between open propellors and Kort nozzle-enclosed propellors is less than 10 percent.

The significance of propellor flow rates depends on the river flow rate and cross-sectional area at a particular place along the river. For discharge, the flow duration values used are for Meredosia at mile 71.2 on the Illinois River and for Keokuk, Iowa, at mile 364.1 on the Mississippi River. The percent of the river flow drawn through the propellors is given in table 11 for three propellor flow rates and four river flow rates at each station. The flows exceeded 20 and 80 percent of the time were chosen to represent high- and low-flow conditions, respectively. The long-term average flow and the median or 50m percentile flow were chosen to

Table 11. Percentage of River Flow Passing through the Propellor Jets

	Riverflow,	*Percent time*	*Propellor flow, m^3/s*		
	m^3/s	*exceeded*	*15*	*45*	*75*
A. Illinois River at Meredosia	220	80	6.8	20.5	34.1
	430	50	3.5	10.5	17.4
	625 (Avg)	36	2.4	7.2	12.0
	960	20	1.6	4.7	7.8
B. Mississippi River at Keokuk	780	80	1.9	5.8	9.6
	1360	50	1.1	3.3	5.5
	1810 (Avg)	37	0.8	2.5	4.1
	2600	20	0.4	1.2	2.9

represent near-average flow conditions. Towboat propellors will pass less than 10 percent of the Mississippi River flows 80 percent of the time at Keokuk or any location downstream of Lock and Dam 19 at Keokuk. Meredosia is the downstream gaging station on the Illinois, and 3,000 HP towboats (the average observed at mile 50) will pass over 20 percent of the river flow through the propellors 20 percent of the time. The percentage will be higher at locations upstream of Meredosia.

Propellor Intake Area. Another parameter that illustrates the possible effect of propellor jet flow on the river is the ratio of intake area to river cross-sectional area. The "intake" area depends on the velocity of approach, which is the speed of the tow relative to the water. For the ranges of steady speed movement of barge convoys given in table 10, the ratio of "intake" area varies from about 1.2 up to about 4 times the area swept by the propellors. However, this area increases dramatically to around 1,000 times the propellor area as the speed approaches zero.

The three channel sizes used in figure 12 and table 10 will be used again to give a range of the ratio between intake area and channel area for steady speed. The most constricted channel is 3.66 m deep by 183 m wide with an area of 670 m^2. The intermediate channel is 4.57 m deep by 183 m wide with an area of 836 m^2. The least constricted channel is 6.10 m deep by 305 m wide with an area of 1,860 m^2. The English sizes are: 1) 12 by 600 ft, 7,200 ft^2; 2) 15 by 600 ft, 9,000 ft^2; and 3) 20 by 1,000 ft, 20,000 ft^2. Table 12 summarizes the ratio between the intake area and channel area in percent for three towboat horsepowers at speeds through the water from 1 to 6 m/s (2.2 to 13.4 mph) in each of the three channels. A 1,000 HP towboat entrains less than 2.25 percent of the river area. A 5,000 HP towboat entrains as much as 11.2 percent of the river area. In severely constricted reaches these percentages will be higher than those in table 12. At very low speeds and high power settings, the ratio will be much higher even for small towboats in large channels.

Propellor Jet Velocities. Fluid jets, including ship propellor jets, have been the subject of much research by many scientists. However, much of the research does not adequately treat the problem of the proximity of inland waterway towboat propellors to the water surface and the fact that this makes the propellor jet a wall jet, i.e., a jet that is attached to a nearby surface. Albertson et al. (1950) conducted a basic jet study on free jet expansion in infinite fluids. Propellor jets of boats on rivers have five important differences from free jets: 1) the channel bottom and sides and water surface confine the jet and limit entrainment, 2) a moving jet expands in an already moving flow field, 3) there are significant rotational and radial velocities in a propellor jet, 4) the rudder divides the jet, and 5) both open propellors and nozzle-surrounded propellors differ from the orifice used in laboratory research. Any number of researchers have reported on studies of ship propellor jet diffusion and velocity distributions.

Table 12. Ratio of Intake Area to Channel Cross-Sectional Area, percent

Propellor			*Tow speed relative to water, m/s*					
HP	*Flow, m^3/s*	*Area, m^2*	*1*	*2*	*3*	*4*	5	*6*
A. 3.66 m deep by 183 m wide channel								
1,000	15	1.83	2.24	1.12	0.75	0.56	0.45	0.37
3,000	45	4.11	6.72	3.36	2.24	1.68	1.34	1.12
5,000	75	5.91	11.20	5.60	3.73	2.80	2.24	1.87
B. 4.57 m deep by 183 m wide channel								
1,000	15	1.83	1.79	0.90	0.60	0.45	0.36	0.30
3,000	45	4.11	5.38	2.69	1.79	1.35	1.08	0.90
5,000	75	5.91	8.97	4.48	2.99	2.24	1.79	1.49
C. 6.10 m deep by 305 m wide channel								
1,000	15	1.83	0.81	0.40	0.27	0.20	0.16	0.13
3,000	45	4.11	2.42	1.21	0.81	0.60	0.48	0.40
5,000	75	5.91	4.03	2.02	1.34	1.01	0.81	0.67

Hochstein and Adams (1989) included one such equation in a broader discussion of inland waterway navigation. A relatively complex method which requires a considerable amount of input data was presented by Verhey (1983). For purposes of discussion, the equations of Fuehrer and Romisch (1977, 1987) and Fuehrer et al. (1981) will be used to indicate the general nature of propellor jet diffusion.

They suggest two equations for the initial jet velocity, V_O. The first is:

$$V_O = 1.6\ n\ D_p K_t^{\ 0.5} \tag{17}$$

where n = rotation rate, in revolutions per second; D_p = propellor diameter in m; and K_t = thrust coefficient. Since K_t is rarely known for the actual conditions in the river, they assume K_t = 0.35 to obtain an approximate equation:

$$V_O = 0.95\ n\ D_p \tag{18}$$

which has an error of 20 percent from the value calculated with the correct K_t.

The second equation for V_O includes the power in kw:

$$V_O = C\ (P_{kw}/D_p^{\ 2})^{1/3} \tag{19}$$

where C = 1.48 for open propellors and 1.17 for ducted propellors, and P_{kw}, is the power in kilowatts. This equation gives jet velocities of 10 to 12 m/s for open propellors and 8 to 9 m/s for ducted propellors. The calculation of propellor flow rates from thrust and speed in table 11 can be extended to determine the jet velocity behind the propellor. These calculations give values between 7 and 8 m/s for open propellors and between 7 and 9 m/s for ducted propellors.

Jet diffusion occurs in three regions: initial, free expansion, and constrained expansion. In the initial region, which extends from the plane of the propellor to x = 2.6 D_p, the centerline velocity is V_O. In the free expansion region, $V_{max} = 2.6\ V_O\ (x/D_p)^{-1}$. In the constrained region

$$V_{max} = A\ (x/D_p)^{-a} \tag{20}$$

with the coefficients A and a depending on the geometry of the propulsion system and the channel. For a single propellor with jet expansion limited by the river bottom and water surface, a = 0.6. For twin propellors, the most common system, a = 0.25. Intermediate values are given by Fuehrer and Romisch (1987) for other conditions. They give two values for A:

$$1.88 \exp[-0.092(y/D_p)] \tag{21}$$

for constraint only by bottom and water surface, and

$$1.88 \exp[-0.161 (h_p/D_p)] \tag{22}$$

for the case with a central rudder, where h_p = height of propellor axis above the bottom. In addition to the decrease in axial velocity with distance behind the propellor, the radial distribution of velocity is given by:

$$V_r/V_{max} = \exp[-22.2 (x/r)^2] \tag{23}$$

where x = distance from' plane of propellor and r = radial distance from the axis at distance x. This equation applies only in the free expansion region. Towboat propellors are close to the surface, and most propellor jets probably act as wall jets along the water surface, so this equation is approximate, even in the zone that is not affected by the river bottom.

In free expansion, the jet centerline velocity decreases linearly with distance. For constrained expansion, especially for twin propellors, the centerline velocity decreases much more slowly with the fourth root of the distance. The equation for lateral distribution of velocity given by Fuehrer and Romisch (1987) yields very small values and appears to be wrong. The traditional free jet velocity distribution (Daily and Harleman, 1966) gives a value of $V_{rx} = 0.1\ V_x$ at $r/x = 0.19$.

Assuming a 2.74-m-diameter propellor in 6.10-m-deep water and an initial jet velocity of 10 m/s at $x/D_p = 2.6$, or x = 7.1 m, the centerline velocity, V_x, will decrease to 2.6 m/s at $x/D_p = 10$ for the free expansion, but to 7.1 m/s for twin propellors near the water surface. At this location, 27.4 m behind the propellors, the velocity would be 0.12 V_x at the river bed.

This discussion of tow drag and propulsion and propellor flow conditions has been fairly extensive. It shows the general nature of the relationships among tow size, towboat HP, and channel size for steady movement along a waterway. The propellor effects include flow rate, intake area, and jet velocities. Only one of many empirical approaches to jet velocity was given. Verhey (1983) presented the most detailed memod yet proposed, but it requires more data and computation than other methods. Maneuvering, especially starting from a stop or stopping a moving tow, will increase the value of most of the parameters discussed.

IDENTIFICATION OF BEST APPROACHES TO DETERMINE RELATIONSfflPS BETWEEN TOW CHARACTERISTICS AND PHYSICAL EFFECTS

The parameters discussed above describe the physical effects of vessel movement and propulsion on the riverine ecosystem. The target variables given in table 4 can each be affected by the vessel size, shape, speed, and distance as well as by bathymetry, ambient velocity, turbulence, and sediment concentration.

One approach is to make exhaustive field measurements of every parameter under a variety of conditions. Another is to conduct laboratory studies of a similarly comprehensive nature. A third is to develop theoretical or numerical models of all the pertinent phenomena. Each of these approaches has much to offer, but each has limitations in terms of time, cost, or effectiveness. The magnitude of the UMRS requires a hybrid approach in which models will be used to extend field and laboratory results to the vast remainder of the river. The target variables from table 4 will be reviewed in a conceptual manner to identify the best approach to further definition and quantification of the effect of barge tows on these variables

Velocity and Turbulence

Velocity in a river naturally varies with stage and discharge, often being different for falling and rising conditions at the same stage or discharge. This ambient velocity varies locally with the depth to the 2/3 power, and is affected by horizontal curvature and local bed and bank structure. The trace of velocity at a point over time shows a variation about an average, or a gradually varying average. This turbulence is a natural part of river flow conditions. It must be determined by direct measurement at a given point and time. The ambient stream velocity will have a turbulence length scale of the same order of magnitude as the channel depth and thus a time scale proportional to the depth divided by the average velocity.

Large-scale bed forms are commonly dunes and generate free-turbulent eddies with a length scale proportional to the dune height. Other factors mat introduce turbulence include other types of irregularities in the river bed or banks; structures such as wing dams, roadway embankments, or bridge piers; and large boulders or fallen trees. These introduce turbulence in relation to their size and the amount of flow that is blocked or deflected.

The movement of a barge tow along the waterway introduces two additional velocity fields to the ambient flow. First there is the displacement or return flow velocity and boundary layer flow associated with the passage of the barge tow through the water. Secondly there is the propellor jet flow, which is of much higher speed and more intense turbulence. Because of the common twin-propellor arrangement, jet rotation, restricted entrainment area, and the placement of the propellor axes near the free surface, the propellor jets do not follow the common pattern of jet expansion.

For experimental quantification of velocities due to the passage of tows and their interaction with the ambient flow in the waterway, two types of regions require different approaches. The near-barge region, which will include velocities and pressures directly under the tow and the flow induced by the propellors, can be studied only in the laboratory. Scaling laws are clearly known, and instrumentation is available to conduct such experiments with a physical model. The regions farther from the barge track on both sides of the river are best studied in the field. An adequate set of sites, channel geometries, and flow conditions can be studied with available instrumentation for velocity and turbulence. Laboratory models would be difficult to use because the Reynolds number is too low and the water depths are too small to obtain hydrodynamic similarity.

Wave Characteristics and Drawdown

Waves and drawdown are placed together because similar instrumentation is needed to measure them. In a sense, drawdown and bow surge are solitary, long-length waves. The existing methods mentioned previously are all empirical, or quasi-theoretical with empirical coefficients. Because of the uncertainties of wave dissipation with distance and the need to separate barge tow waves from wind waves, field studies appear to be the best approach. It is possible that more comprehensive prototype data sets will identify one or two facets of the wave and drawdown phenomena that could be better determined in laboratory studies, though scale effects will probably be present. As for velocity, a moderate number of sites and flow conditions will provide sufficient data to refine existing relationships or define more accurate ones for applications to the entire UMRS.

Concern about the effects of wind waves and recreational boat waves also indicates that field measurements are the best way to obtain comprehensive wave data. Wind waves are measured as part of the daily wave data collection, and wave data are collected for selected recreational craft events. The results of a recent field study of recreational boat waves will be available soon (Bhowmik et al., 1990) and will provide a level 1 model which should be verified with additional data.

Suspended Sediment Concentration

Sediment resuspension and mixing caused by increased velocities, drawdown, and waves resulting from tow passage has been observed many times. However, suspended sediment concentration is the least predictable of the ambient characteristics of streams and rivers. Ambient concentrations of suspended sediment vary from point to point and with time at a single point (Vanoni, 1975). The mechanics of sediment entrainment and suspension involve Reynolds numbers and Froude numbers for both fluid and suspended particles. Thus entrainment and movement of suspended sediment cannot be studied with laboratory scale models.

Consequently field studies are the only possible means to obtain data on the effects of barge tows on changes in suspended sediment concentration due to resuspension and lateral movement. Only three studies of resuspension of sediment by barge tows have been conducted on the UMRS. Johnson (1976) and Karaki and van Hoften (1974) studied resuspension, but they collected samples at rather long intervals. Bhowmik et al. (1981a) collected suspended sediment samples at increased frequencies immediately following tow passages, using depth-integrating samplers.

At this time the methods of obtaining and determining the concentration of suspended sediment in water are labor-intensive and time-consuming. This is true both of the depth- or point-integrating samplers, which collect a single discrete sample for future laboratory analysis, and of pumped point-integrated sampling techniques. For the types of information desired by aquatic biologists, arrays of point-integrated pumped samplers are the best available. However, such sample collection techniques accumulate large numbers of samples for laboratory analysis.

There are some techniques, such as particle counters, that can be used in the laboratory on very small samples with very low concentrations, but these instruments are not suitable for field use. For a given set of particle characteristics, turbidity, which is a measure of light scattering by the particles, is a possible surrogate for concentration. This measurement requires calibration samples for both concentration and particle size distribution. Turbidity is also caused by other small particles, including plankton, and by some dissolved constituents. For some biological effects concentration of sediment may be most important, and for other effects turbidity or light extinction may be most important. These selections of physical factors to use in the biological models will require interaction between scientists and integration of field experiment design with level 2 or level 3 model requirements.

SCALES OF PHYSICAL IMPACT AREAS AND THRESHOLDS FOR BIOLOGICAL IMPACTS

Besides the magnitude and duration of changes in velocity, depth, and suspended sediment concentration, the portion of the riverine habitat or of various habitat classes that will be impacted by barge tow effects is an important factor in the magnitude of the impact on the biota and the ecosystem. The spatial and temporal scales of the impacted areas will be discussed first, after which some thresholds for biological impacts of physical effects will be considered.

Spatial and Temporal Scales

The spatial scale depends on the dimensions of the habitat area of interest and the critical values necessary for significant effects to occur. For instance, depth/draft ratios less than 2 indicate significant effects on velocity beneath the barge tow, on propellor jet velocities impinging on the river bed, and perhaps on return flow velocity. The first two are main channel effects and may need to be considered in depths less than 5.5 m (18 feet). Return-flow velocity extends across the entire channel along with drawdown, so channel border areas are also affected.

Drawdown depends primarily on the blocking factor and is expected when BF > 0.1. Drawdown, however, is most important in channel border areas where a strip of river bank slope will be exposed. For instance, with a bank slope of 1 in 10, a 0.1 m (0.33 ft) drawdown will expose a strip 1 m (3.28 ft) wide along each shoreline for a period equal to the time it takes the tow to pass a point. Typically this will be between 1 and 5 minutes. Another way to view the effect of drawdown is as a strip the length of the tow moving along the river banks at the speed of the tow. The associated bow surge in front of the tow is not considered important. However, the infill wave at the rear end of the drawdown can be abrupt and is associated with the stern waves from the barge convoy.

Dramatic, but not quantified, effects have been observed in side-channel and backwater areas. As the drawdown passes the entry to a side channel or the connecting channel to a backwater, flow out of the area is induced, and it is followed by inflow when the infill wave passes. It is possible mat significant amounts of shallow, gradually sloping bed could be exposed in a backwater area. It is possible for a sloshing or surging action to be set up if the natural period of the backwater corresponds to the period of the drawdown (1 to 5 minutes).

Tow-generated waves will affect the entire water surface. The impact of waves is primarily in the channel border areas where shoaling depths allow wave orbital velocities to impinge on the bed and wave height to increase as wave speed decreases, until the wave breaks in the shore zone. Wave orbital velocities decrease exponentially with distance below the surface. For waves with lengths of about 6 m (20 ft), the ratio of bottom velocity to wave speed is less than 9 percent in a depth of 3 m (10 ft) and less than 1 percent for depths over 5 m (16 ft). As a wave travels toward the shore it slows down and becomes higher and steeper until it breaks. Thus wave-induced velocities are more important near the shore where they can cause bank erosion and resuspension of bed material. If suspension of bed material is the important effect of wave action, a criterion can be derived in terms of water depth and bed material size.

Waves traveling into side channels and backwaters are modified by the geometry of the inlet channel, including its angle to the waves. Because wave speed is a function of depth, waves are refracted as the water depth decreases approaching the shore or a submerged structure, and waves reach shore with their crests nearly parallel to the shoreline, no matter what their alignment has been in the deeper water of the channel.

Another characteristic of waves is that they are reflected from the river banks. Natural banks with gradual slopes reflect only a small percentage of the wave energy. Steeper riprapped banks will also have low reflectivities. However, vertical surfaces such as sea walls or barges reflect nearly 100 percent of the wave energy, and the reflected and incident waves interact to cause a confused water surface.

Thus, though the entire water surface is subjected to wave action, significant impacts are likely only in areas in which the bottom velocities are high enough to suspend sediment, aquatic plants are damaged, or erosion occurs. Temporal scales are determined by the time of passage of the tow and the period in which the incident and reflected waves are of a height sufficient to impact the ecosystem. This time scale is on the order of 5 to 15 minutes, depending on local geometry.

Thus velocity, wave action, and drawdown effects all have time scales of less than about 15 minutes. The time scale for resuspended sediment is much longer, and the entire river volume may be subject to increased sediment concentrations and modified sediment deposition. Available data (Adams et al., 1989; Adams and Delisio, 1990) indicate that increased concentrations can be as much as 500 mg/L and can last for more than 90 minutes after tow passage on the Illinois River. Their results also show mat the increase in concentration is greater near the bottom and shore.

Identification of Physical-Biological Relationships

From the viewpoints of fluid mechanics and hydraulics, the previous sections complete the introduction to the physical effects of navigation in constricted waterways such as those of the UMRS. From the viewpoints of aquatic ecology and biology, there needs to be a linkage between the physical effects and the robustness, mobility, or adaptability of the plants and animals in the river. This is best done by means of a conceptual model approach. This is relatively easy for a single event, but it is much more difficult for the cumulative impact of multiple events or increased numbers of events per unit time. However, this report is directed at the effect of a single tow passage event.

K.S. Lubinski (EMTC, Onalaska, WI, personal communication, 1990) outlined a procedure for developing conceptual models in a workshop on ichthyoplankton (larval and juvenile fish). According to his terminology, the previous sections dealt with level 1 models. Figure 13 illustrates the three model levels: from tow passage to physical forces (level 1), to impact on individual organisms (level 2), and finally to effects on populations (level 3). Level 2 models combine a level 1 model with tolerance or disturbance criteria for different types of organisms. Level 3 models extend the level 2 model results from an individual scale to a population scale effect.

For example, a level 1 model might determine that 10 percent of the river cross section is drawn through the propellors and might give a probability mat the water from a particular habitat area will be entrained. The level 2 model will give the percentage of eggs or larval fish of a given species that will be killed or injured by passage through the propellors, based on temporal and spatial distribution and density of fish eggs and larvae. The level 3 models will take the effect of a single tow on a single species to the cumulative effect of tow movement on young-of-the-year numbers and finally on adult populations of all common species of fish in the reach over a given period.

Another example might be the impact of tow-generated waves on mussels in a channel border habitat. The level 1 model would contain several elements to 1) estimate the height and duration of waves reaching the mussel bed from a tow passing a given distance away, 2) estimate the resuspension of sediment by the waves, and 3) estimate the duration of increased sediment concentration. The level 2 model would use the increased sediment concentration and its duration to determine the reduction in feeding success by a given size or age class of a particular species of mussel. The level 3 model would extend this to the effect of commercial navigation or recreational boating on the population characteristics of the mussel bed with predicted traffic scenarios for tows and recreational boats.

Conceptual models help to guide the problem-solving process but can also appear much simpler than the actual solution of each model level and the linkages between levels. This is particularly the case wim the linkages between a physical effect and a biological impact, and the linkages between impacts on individual organisms and estimates of population or community trends. Indeed, these two linkages are the least understood for many plants and animals in the riverine ecosystem, and will be the most difficult steps to accomplish in the models. The only

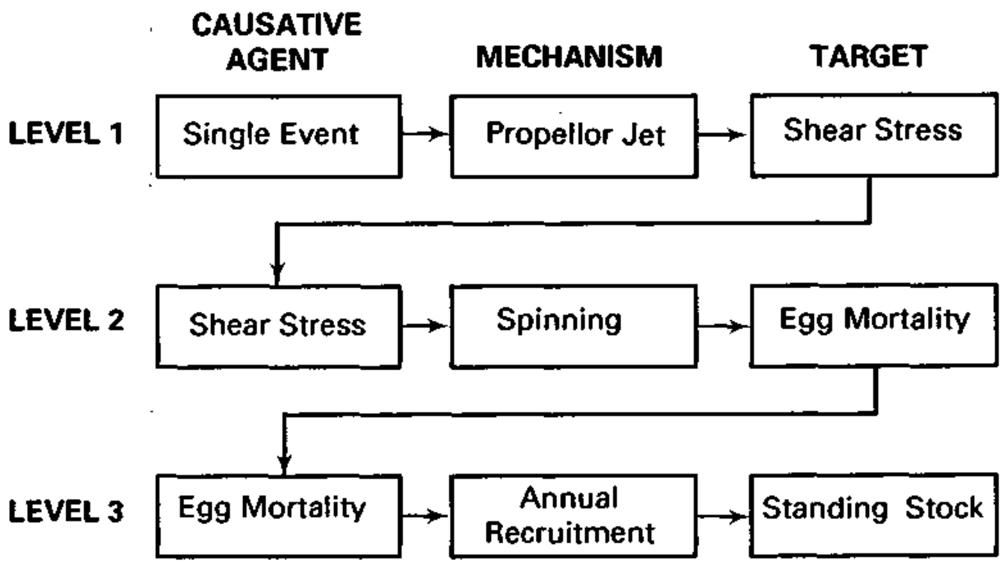

Figure 13. Conceptual model levels for single barge tow passage event effects

thing more difficult than modeling these linkages may be obtaining field or laboratory data to verify or confirm the models.

SUMMARY

Vessel traffic and river environment descriptor variables have been listed and the magnitudes of their ranges defined. Target physical variables were selected on the basis of their likelihood of having biological effects. The total number of variables is 34, not including several basic quantities like water density and viscosity, which were introduced in a discussion of dimensional analysis.

Dimensional analysis was used as a rational approach to a conceptual model of the physical impacts of navigation on constricted waterways. Eight parameters characterizing the physical effects of tow passages were discussed in detail. Because of its complexity, special attention was given to the effects of the propulsion system.

Study approaches to determine the relationships between tow passage characteristics and typical target physical variables were treated from the perspective of hydraulic engineering. The basics of scale for physical effects were presented, but the appropriate scale for the biological aspects remains unknown. A final section presented an approach mat involves three levels of model to conceptually relate tow passage to population scale effects on the biota of the riverine ecosystem.

ACKNOWLEDGMENTS

This research was done as part of a project supported by the U.S. Army Corps of Engineers through the Environmental Management Program for the Upper Mississippi River System. The funding was provided through the Environmental Management Technical Center, Onalaska, Wisconsin, and the Illinois Department of Conservation. Kenneth S. Lubinski is the project manger for the U.S. Fish and Wildlife Service and Bill Donels is the project coordinator for the Illinois Department of Conservation. Nani G. Bhowmik is Project Director for the Illinois State Water Survey. Kathleen J. Brown typed the camera-ready text, Linda Hascall prepared the graphics, and Gail Taylor edited the report.

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